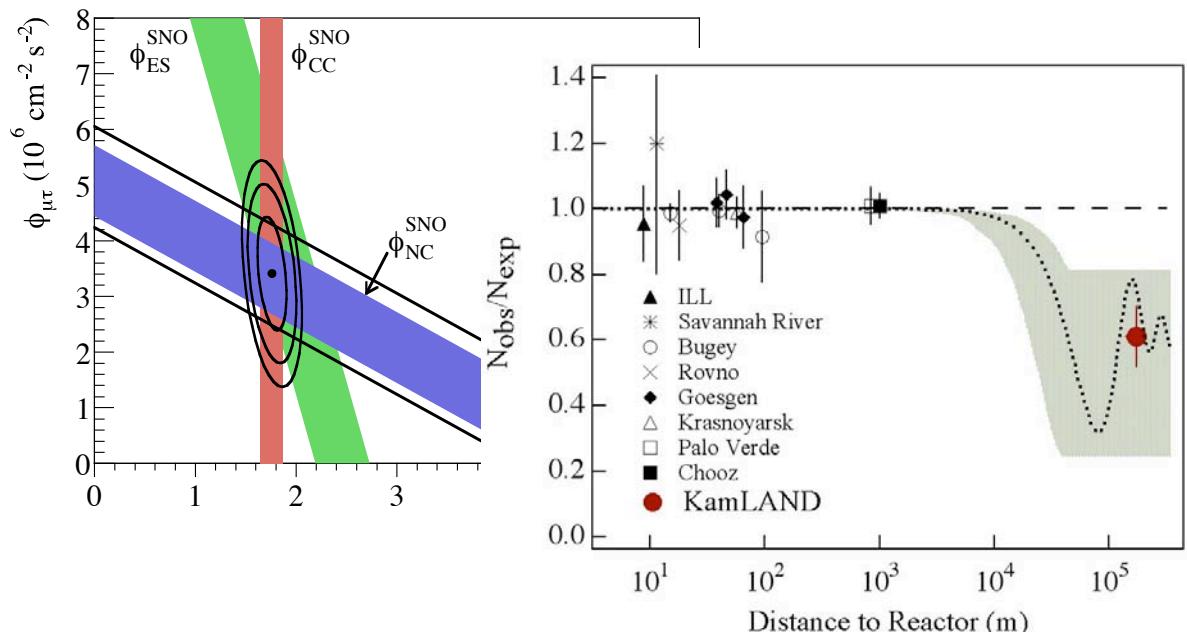
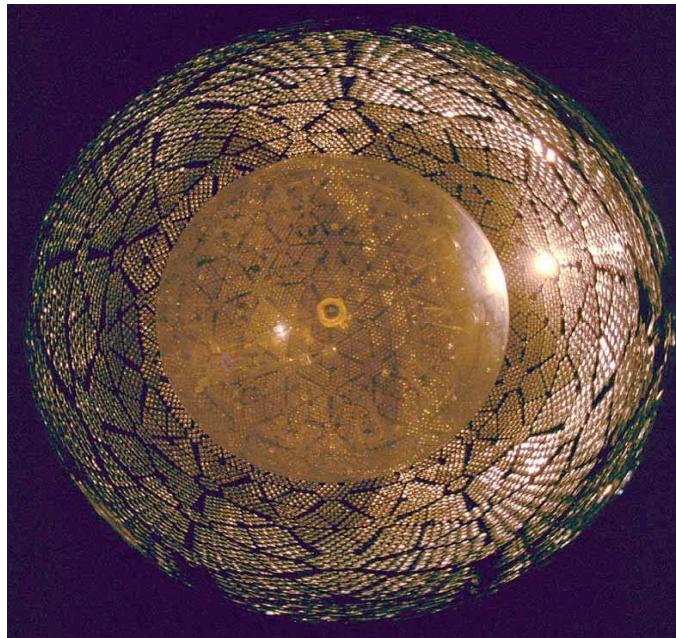


Evidence for Massive Neutrinos and Neutrino Oscillation

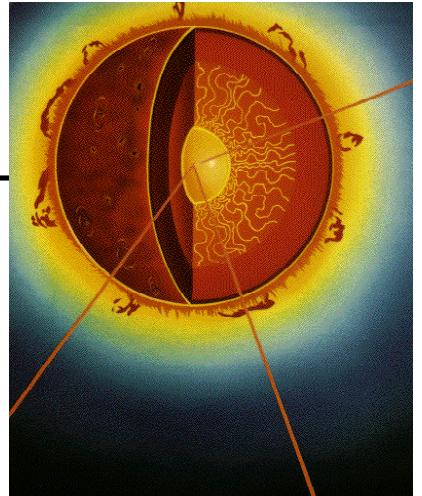
The Resolution of the Solar Neutrino Problem at SNO and KamLAND

Karsten M. Heeger

Lawrence Berkeley National Laboratory



Birth of Neutrino Astrophysics

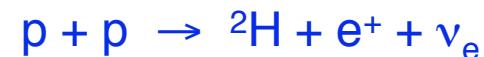


1854 van Helmholtz postulates gravitational energy

1920 Eddington proposes p + p fusion

"We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place."

1938 Bethe & Critchfield



1946 Pontecorvo, 1949 Alvarez



propose neutrino detection through

Using solar ν's to probe the Sun ...

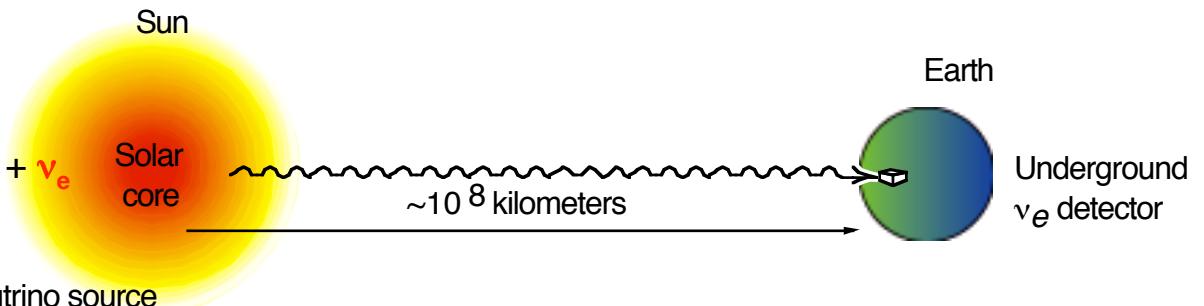
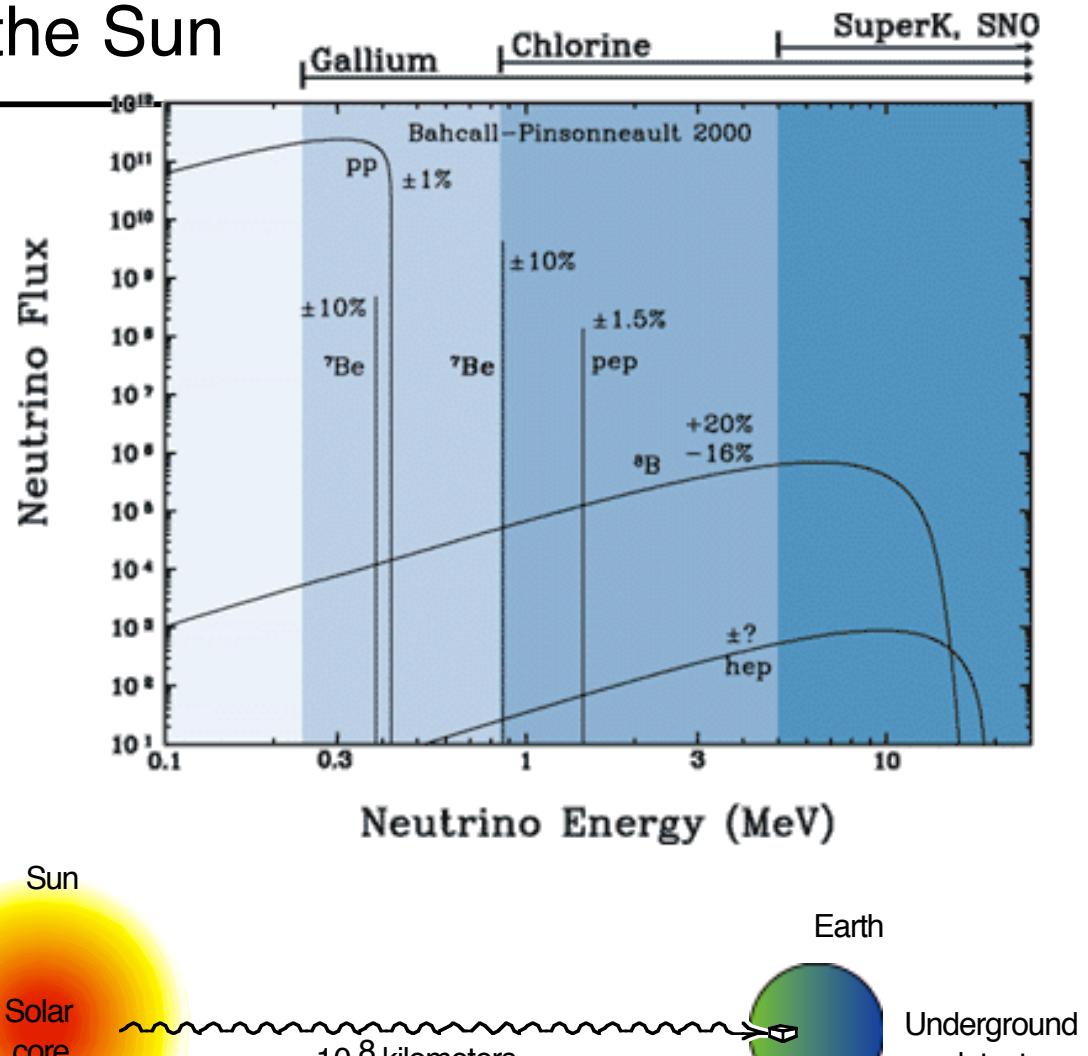
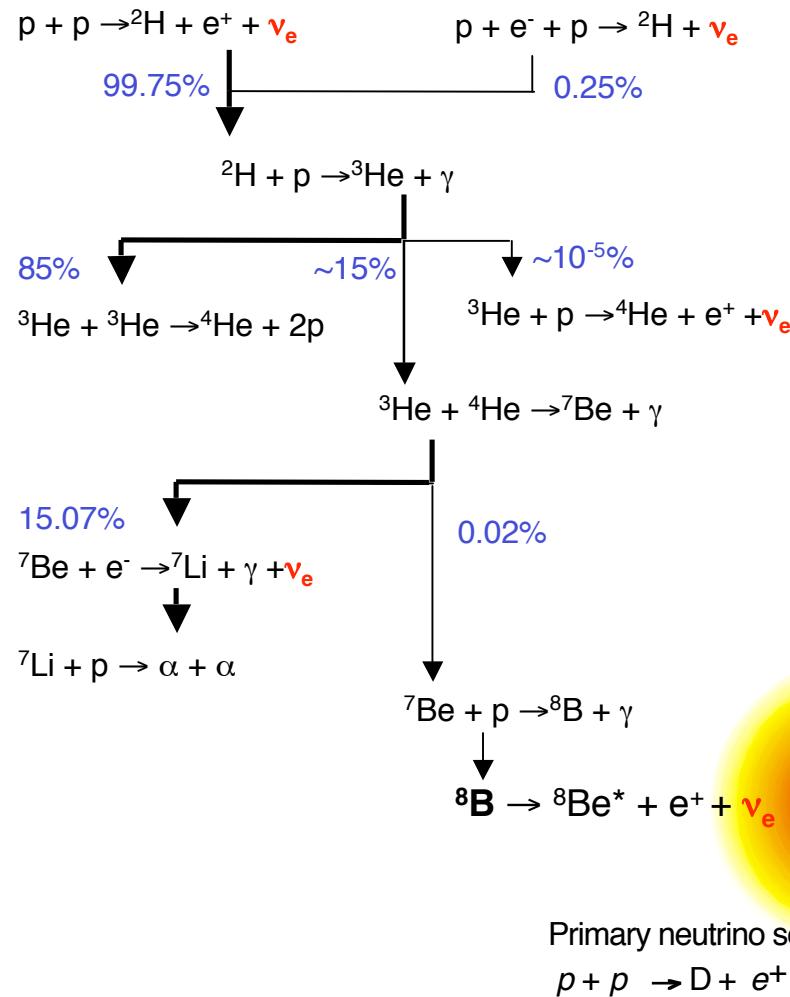
1960's Ray Davis builds chlorine detector

John Bahcall, generates SSM & solar ν flux predictions

"...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars..."

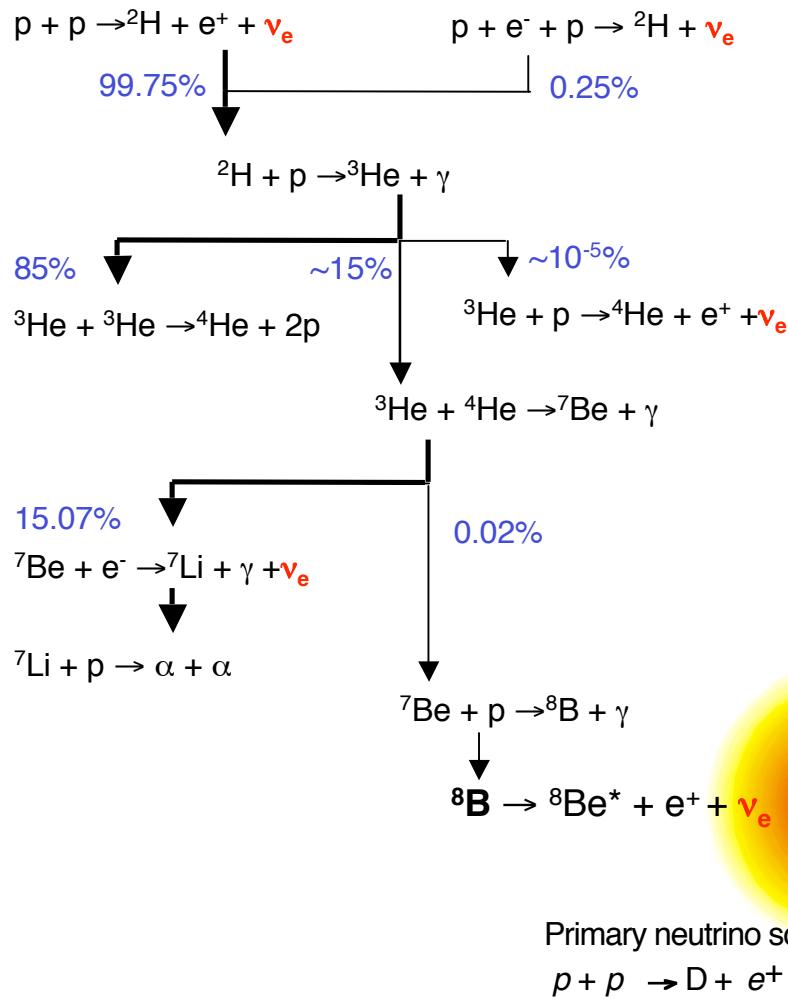
Neutrino Production in the Sun

Light Element Fusion Reactions



Neutrino Production in the Sun

Light Element Fusion Reactions



Energy from hydrogen burning:

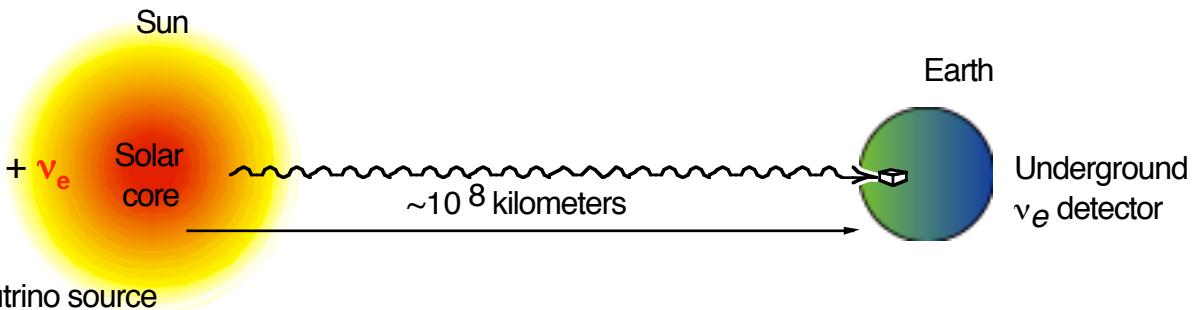
$$4 p + 2 e^- \rightarrow ^4\text{He} + 2\nu_e + 26.731 \text{ MeV}$$

Measured power reaching Earth:

$$137 \text{ mW cm}^{-2} = 8.53 \times 10^{11} \text{ MeV cm}^{-2} \text{ s}^{-1}$$

So, the solar electron neutrino flux is

$$\frac{2 \times 8.53 \times 10^{11}}{26.731} = 6.38 \times 10^{10} \nu_e \text{ cm}^{-2} \text{ s}^{-1}$$



Neutrino Astrophysics

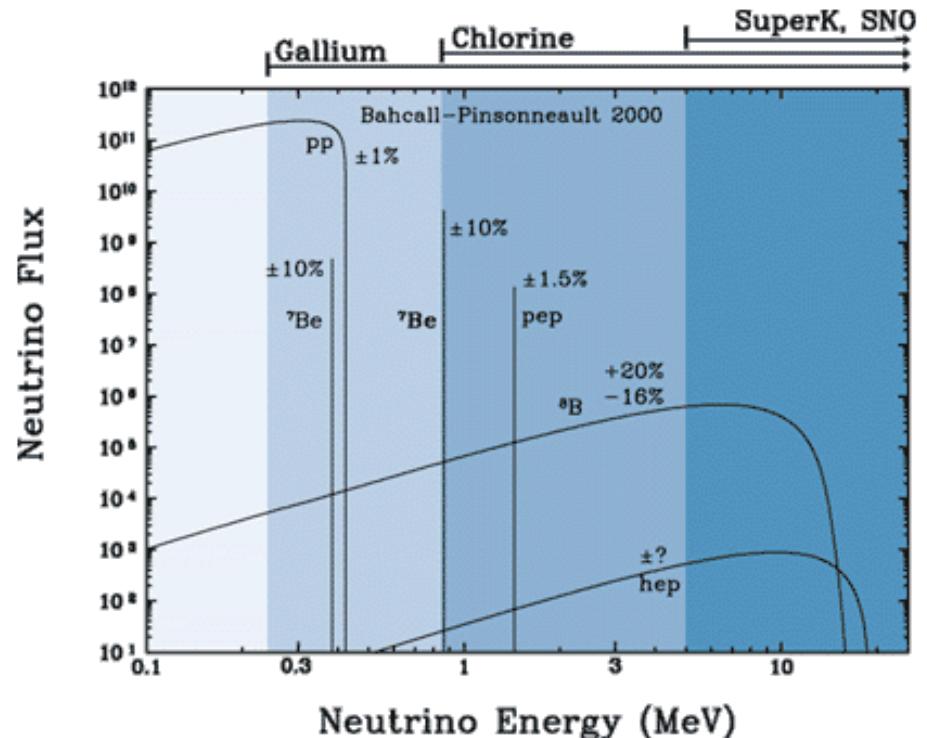
Solar Neutrino Flux Measurements

1960's

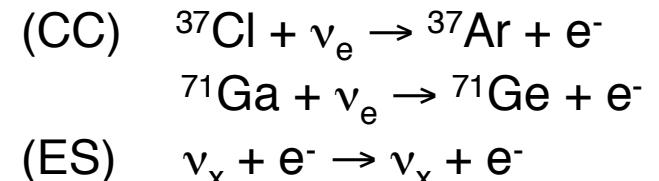
- Ray Davis' Chlorine detector
- First Solar Model calculations

For 30 years

CC and ES measurements of solar ν

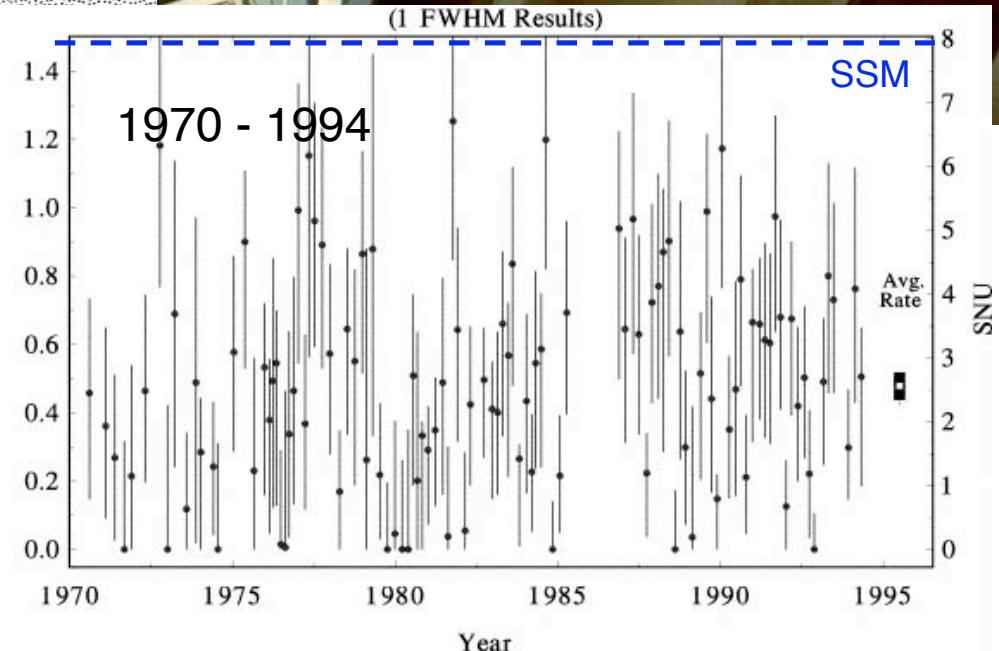
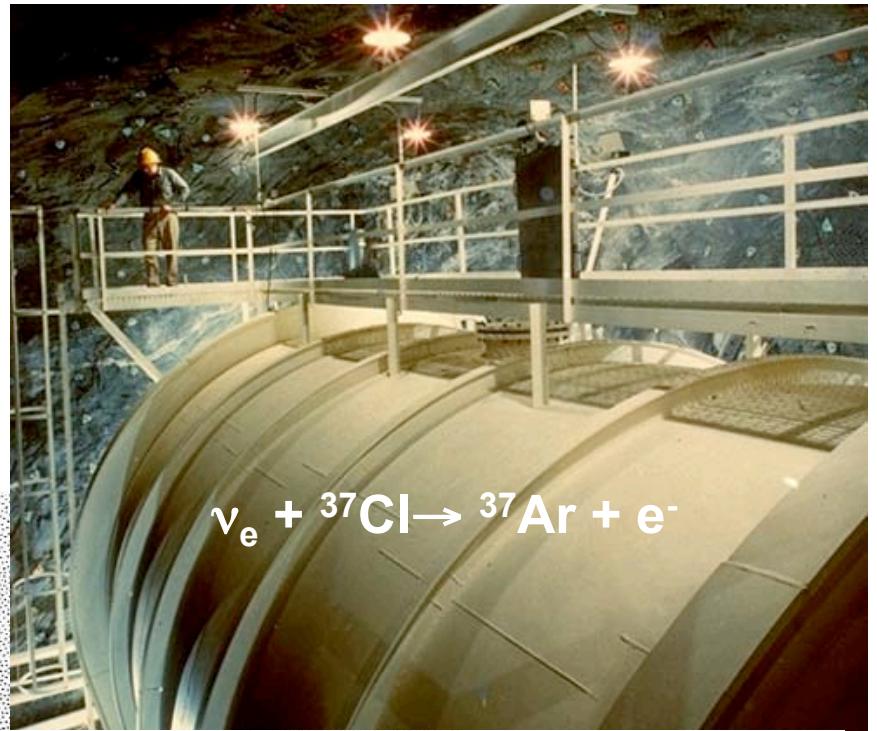
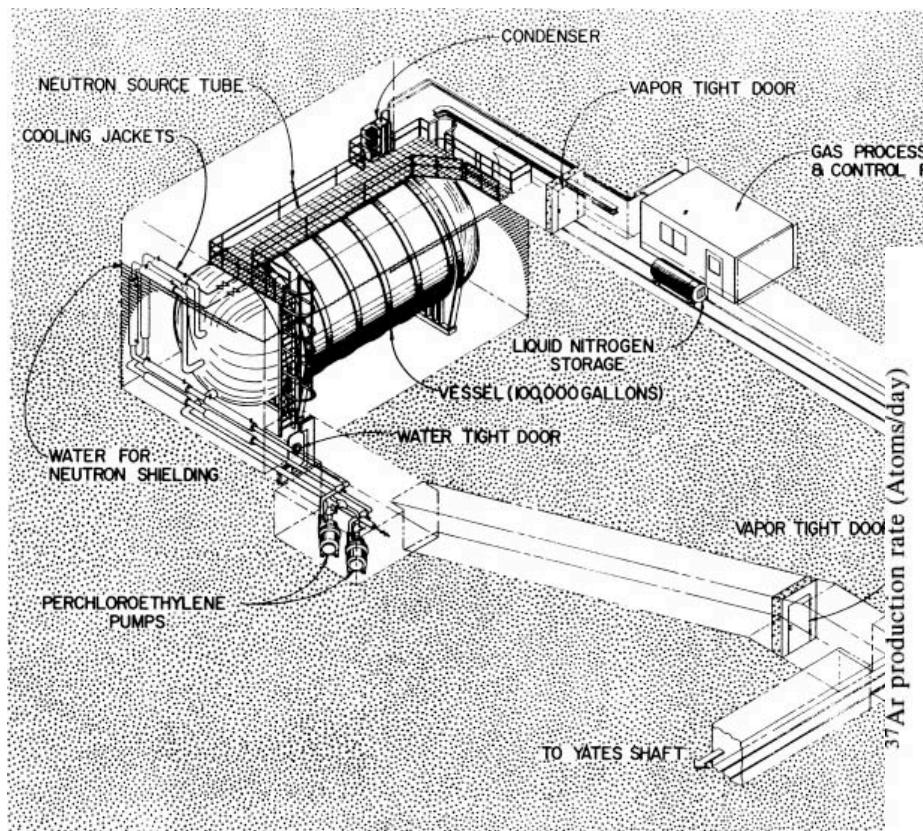


Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

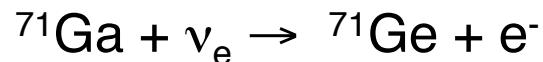


→ Data are incompatible with standard and non-standard solar models

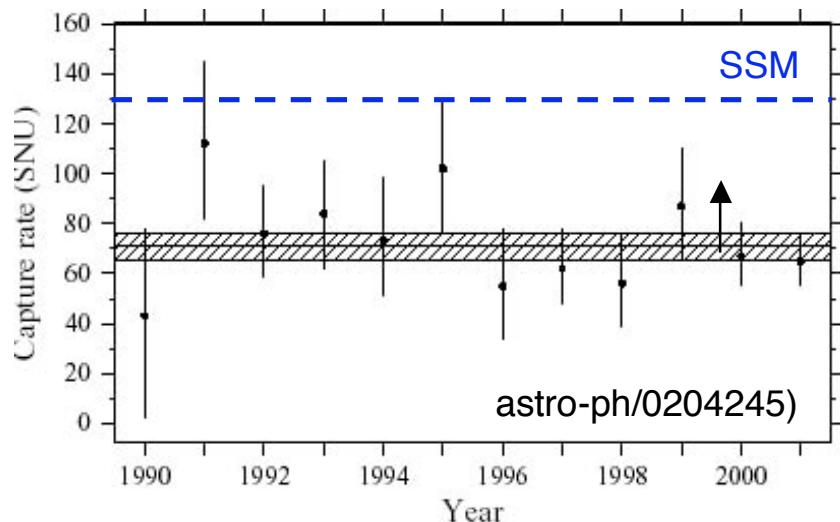
Cl-Ar Solar Neutrino Experiment at Homestake



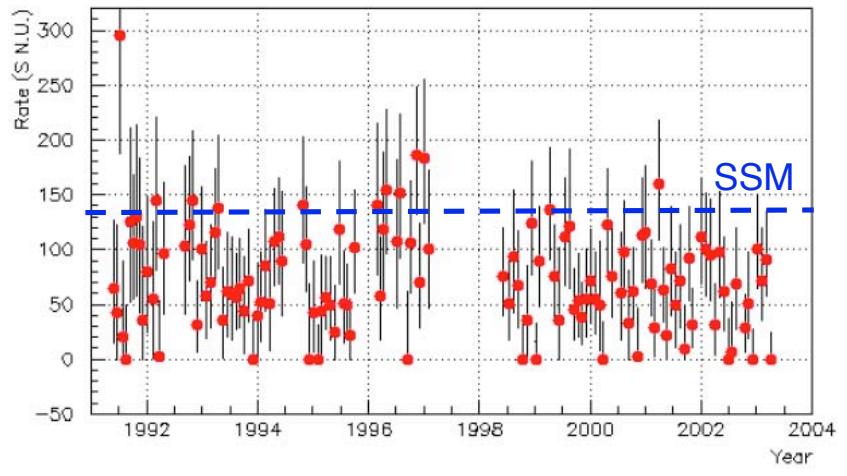
Gallium Measurements



SAGE



GALLEX



GNO

GNO
58 solar runs

Two independent experiments

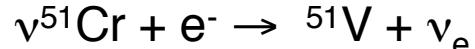
SAGE

Data/SSM = 0.55 ± 0.05

GALLEX

Data/SSM = 0.57 ± 0.05

Both experiments performed source tests

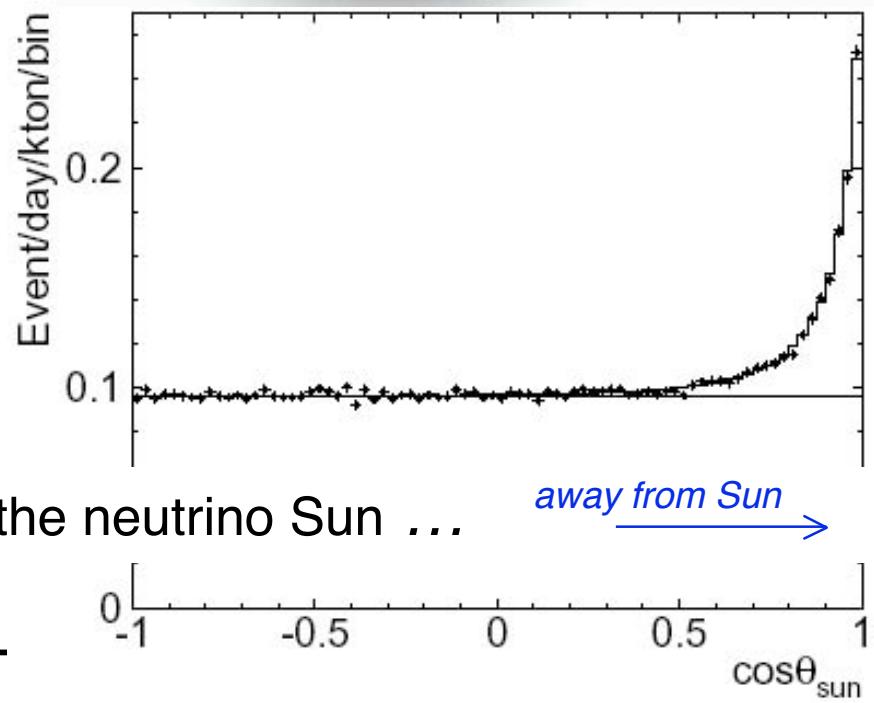
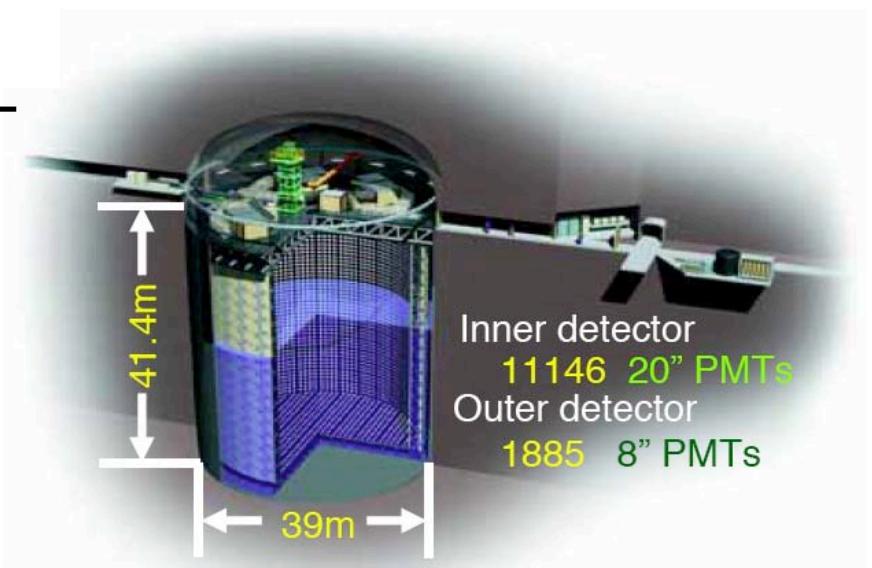
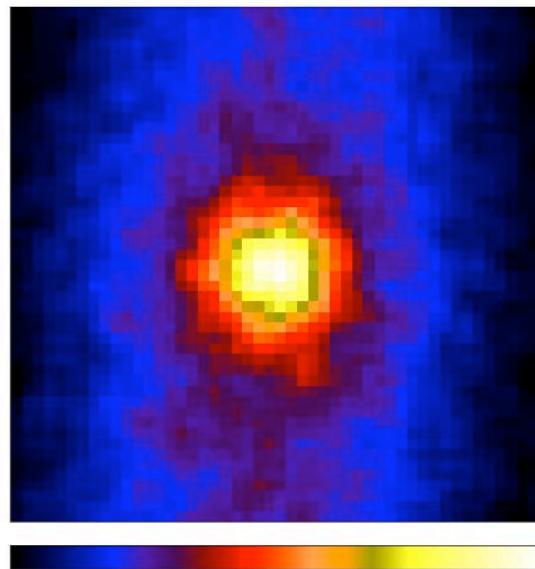


High-Statistics Solar Neutrino Observations at Super-Kamiokande

Elastic Scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$

$$\Phi^{\text{ES}} = 2.32 \pm 0.03 \begin{array}{l} +0.08 \\ -0.07 \end{array} \quad (\text{stat}) \quad (\text{sys.}) \quad (10^6 \text{ cm}^{-2} \text{ s}^{-1})$$

$$\text{Data/SSM} = 0.451 \pm 0.005 \begin{array}{l} +0.016 \\ -0.014 \end{array} \quad (\text{stat}) \quad (\text{sys.})$$



Observing the neutrino Sun ...

Nobel Prize for the Detection of Cosmic Neutrinos



The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"



Raymond Davis Jr.



Masatoshi Koshiba



Riccardo Giacconi

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"



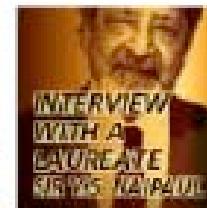
ALFRED NOBEL
1833-1896



**DAVID
BLAUM**



**TIME-LAPSE
VIDEO:
MENGEL
BONHOET**



**INTERVIEW
WITH A
LAUREATE
MASATOSHI KOSHIBA**

⊕ 1/4 of the prize
USA

University of
Pennsylvania
Philadelphia, PA, USA
b. 1914

⊕ 1/4 of the prize
Japan

University of Tokyo
Tokyo, Japan
b. 1926

⊕ 1/2 of the prize
USA
Associated
Universities Inc.
Washington, DC, USA
b. 1931
(in Genoa, Italy)

What is the Solution?

Experimental Errors?

But all experiments show similar effect.

Astrophysics wrong?

Perhaps, but even with all fluxes as free parameters, cannot reproduce the data.

New neutrino physics such as oscillations?

In 1968 Pontecorvo suggests that if lepton number is not conserved, ν_e could change into ν_μ . Since the Cl-Ar detector was sensitive only to ν_e , it would appear that the flux was low.

What is the Solution?

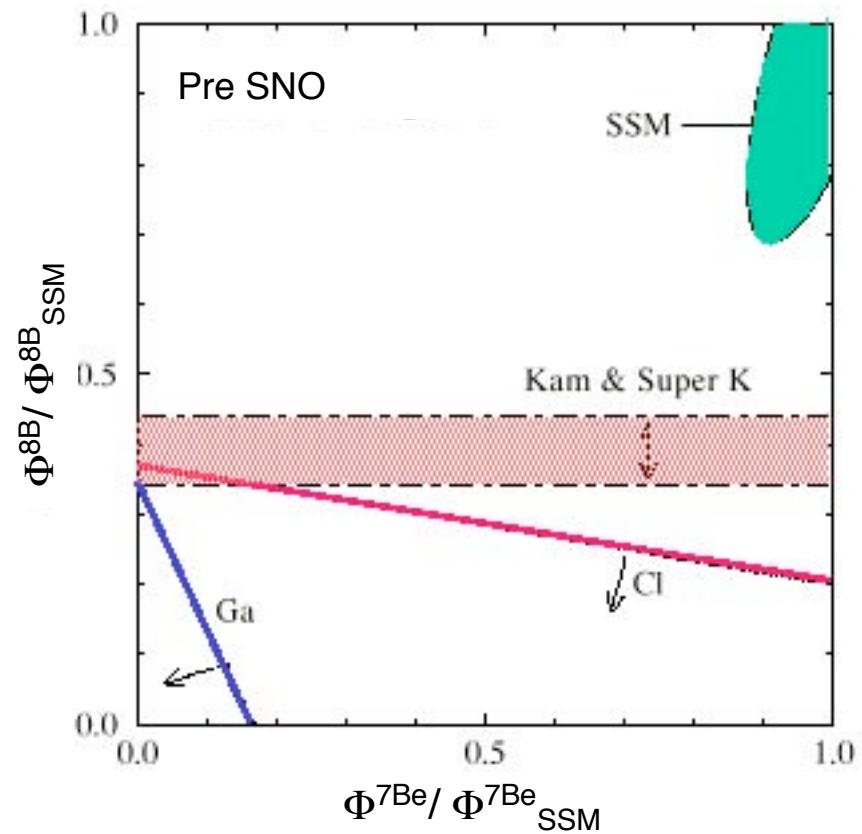
Experimental Errors?

But all experiments show similar effect.

Data are incompatible with standard and non-standard solar models!

$P_{MSM} < 1.7\%$ at 95% CL

KMH, Robertson PRL 77:3270 (1996)



Beyond the Standard Model: Neutrino Mass and Mixing

Neutrino Flavor Transformation through Oscillations

If neutrinos have mass leptons can mix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstates are a mixture of mass eigenstates

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

States evolve with time or distance

$$\nu_e = U_{e1}e^{-iE_1 t}\nu_1 + U_{e2}e^{-iE_2 t}\nu_2 + U_{e3}e^{-iE_3 t}\nu_3$$

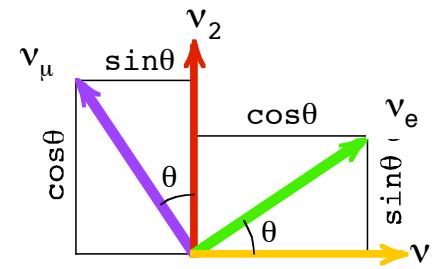
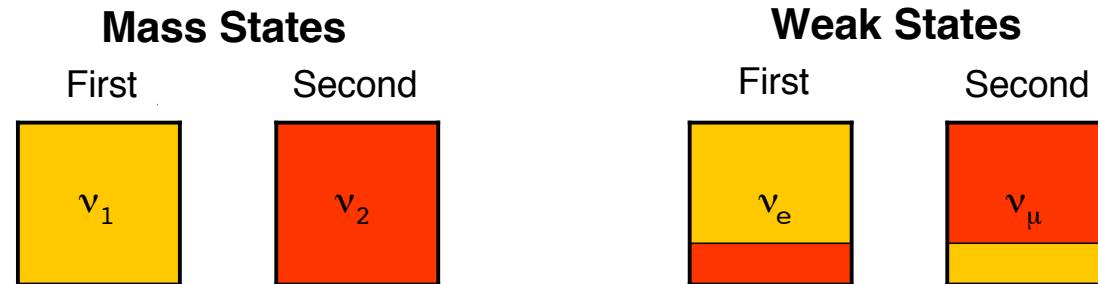
Matter Enhanced Oscillations (MSW)

Neutrinos in matter can acquire effective mass through forward scattering,
 ν_e can undergo both CC and NC scattering

→ MSW ν oscillations are dependent on ν energy and density of matter

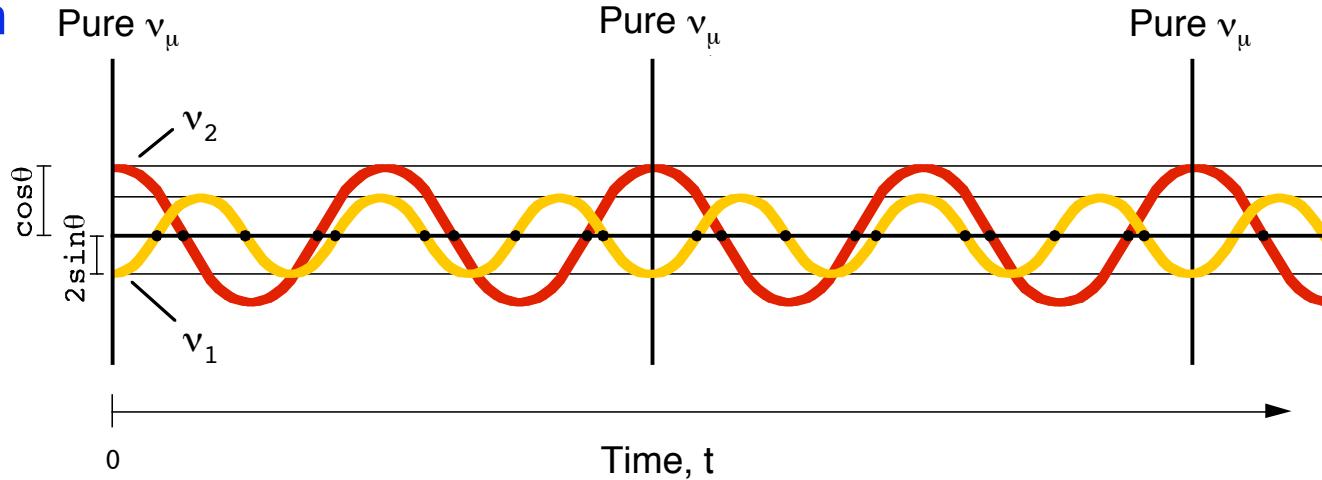
Neutrino Oscillations

Neutrino States



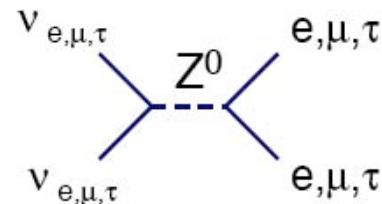
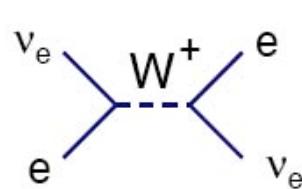
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ 2\sin\theta & \cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Time Evolution



Hypothesis: Matter-Enhanced Neutrino Oscillations in the Sun

Neutrinos produced in weak state ν_e



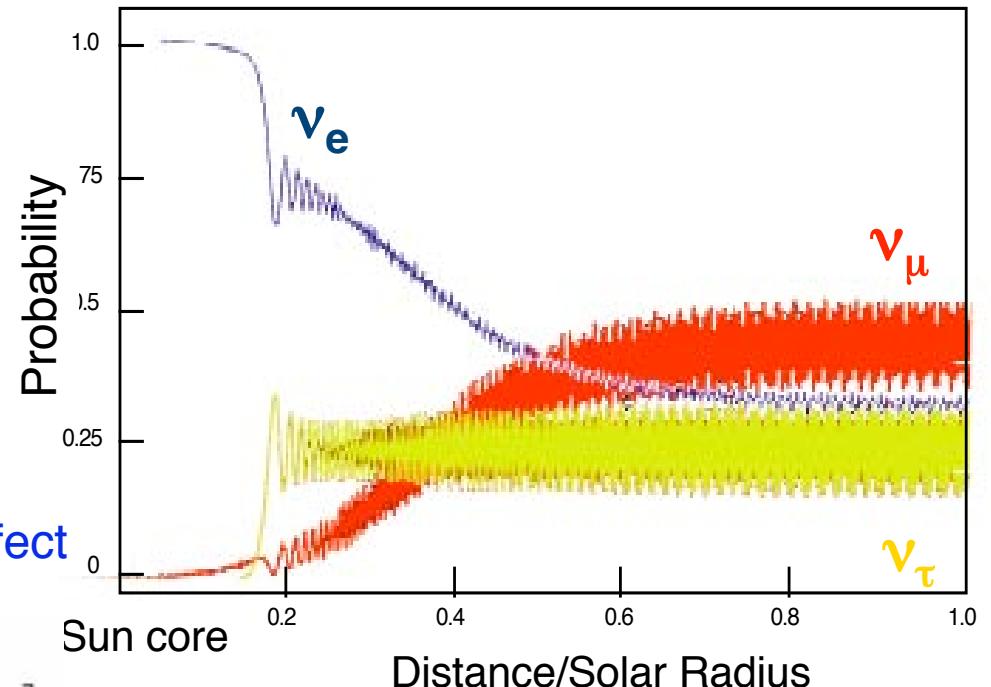
Flavor conversion can be a resonant effect in matter:

Mikeheyev - Smirnov - Wolfenstein Effect

$$\mathcal{H} = \mathcal{H}_V + \mathcal{H}_M(r)$$

$$= \frac{\Delta m_\odot^2}{4E} \begin{bmatrix} -\cos 2\theta_\odot & \sin 2\theta_\odot \\ \sin 2\theta_\odot & \cos 2\theta_\odot \end{bmatrix} + \begin{bmatrix} V(r) & 0 \\ 0 & 0 \end{bmatrix}$$

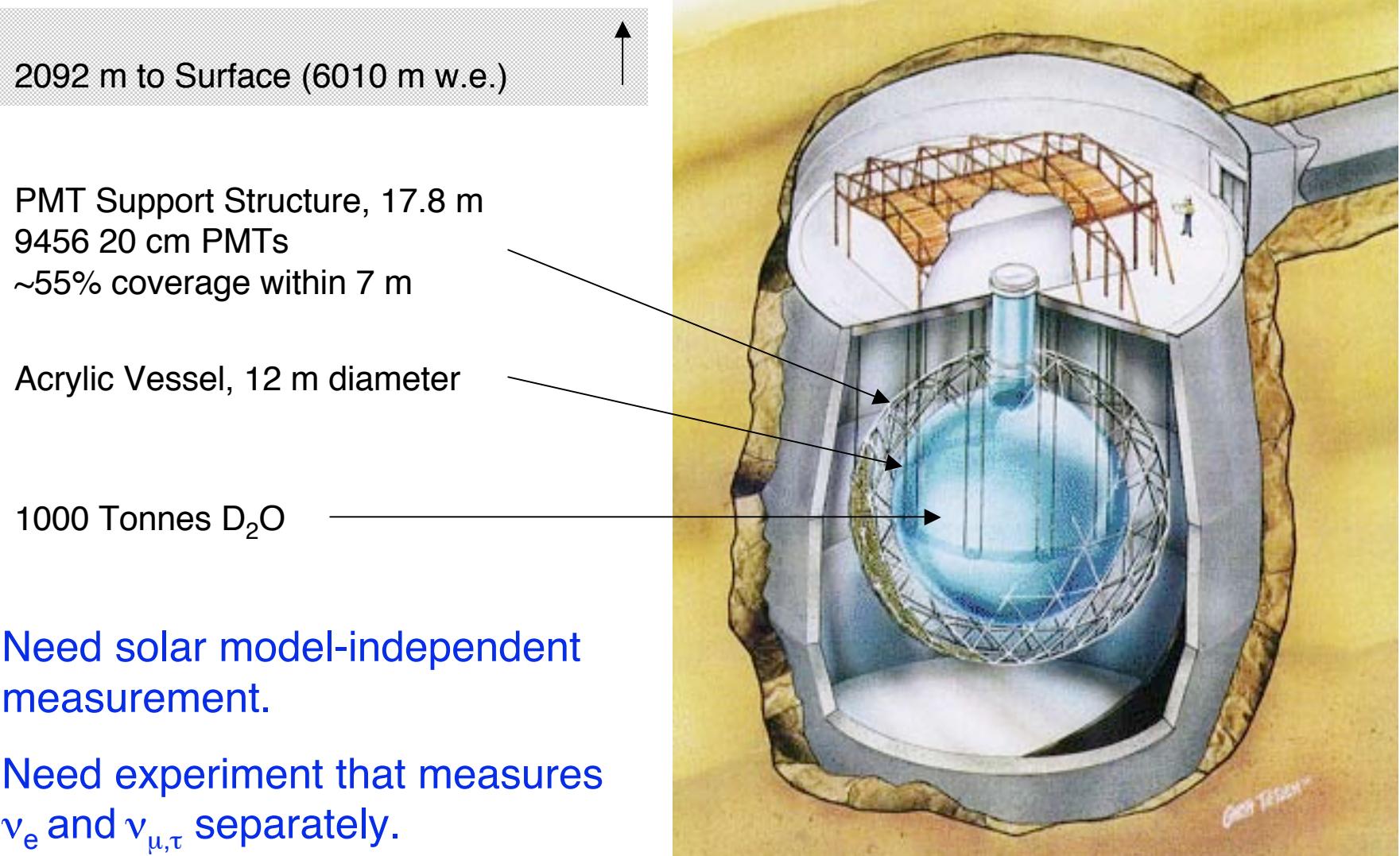
$$V = \sqrt{2} G_F N_e$$



Superposition of mass states may change through the MSW resonance effect

→ Solar neutrino flux detected on Earth consists of $\nu_e + \nu_{\mu,\tau}$

Sudbury Neutrino Observatory



Heavy Water from Bruce Plant



Construction of the Sudbury Neutrino Observatory



40 The Toronto Sun, Friday January 5, 1990

\$61M SUDBURY OBSERVATORY

Scientists get the shaft

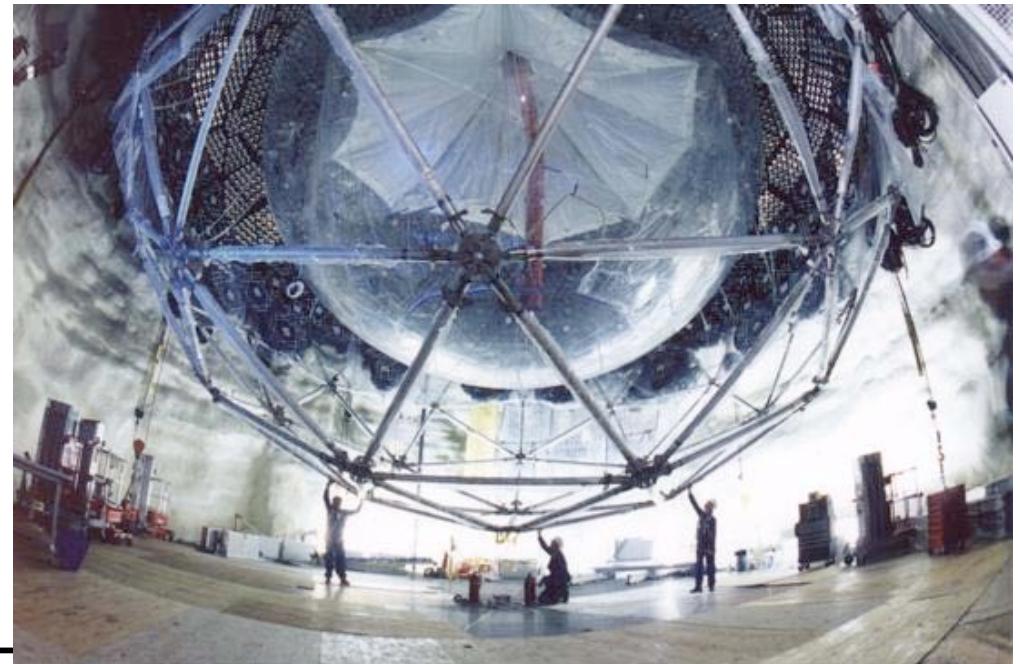
OTTAWA (Staff-CP) — Scientists will study the nature of the universe with a \$61-million observatory to be built in a Sudbury mine shaft.

The observatory is to

five years measuring drops in a bucket.

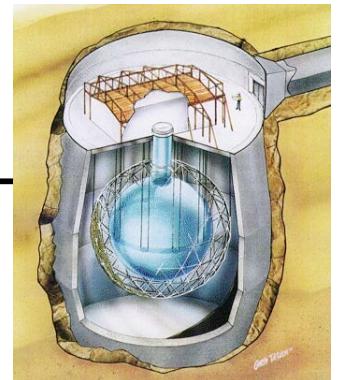
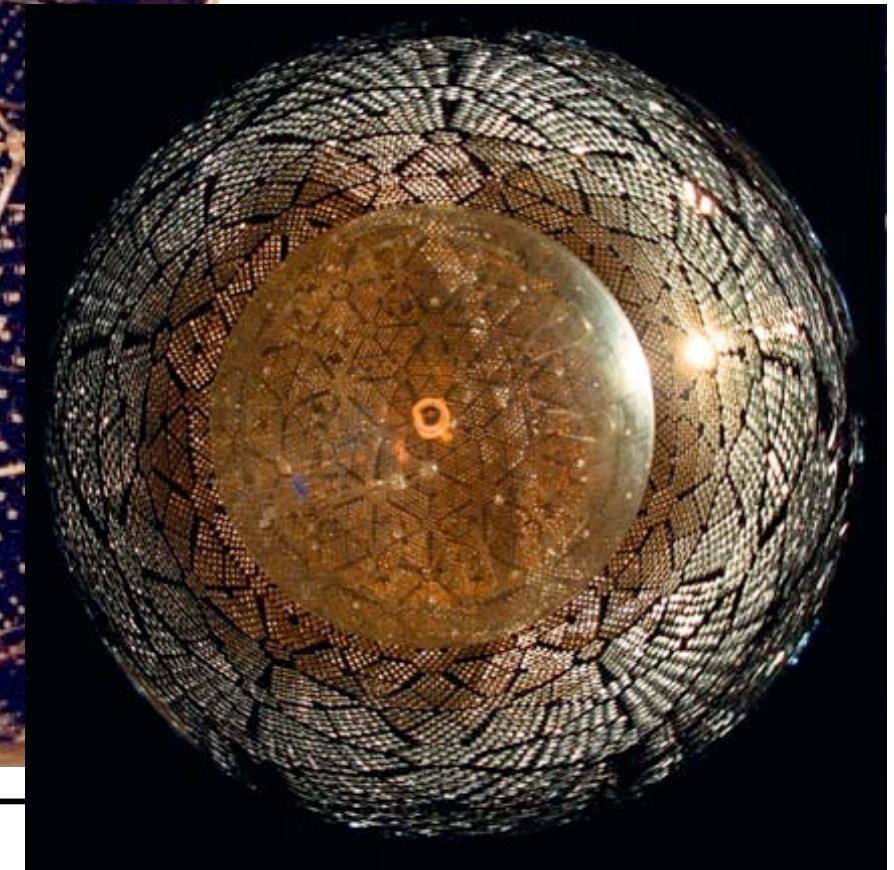
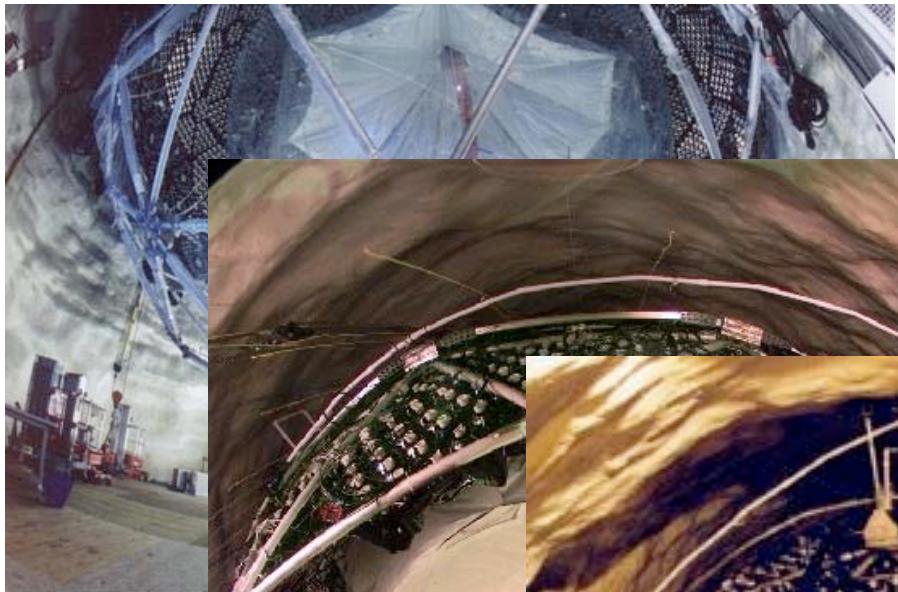
The bucket — to be built over the next four years — will be a 1,000-

tonne pool of heavy water. The drops — up to 10,000 a year — will show as flashes of light created when neutrinos react with heavy water.



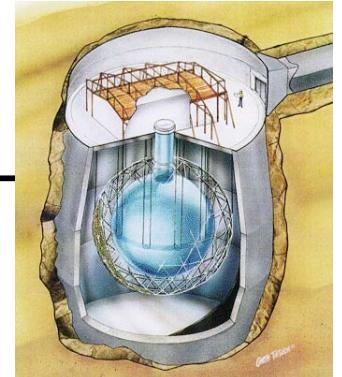
2004

Construction of SNO

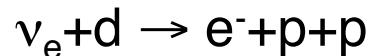


Neutrino Detection in SNO

Neutrino Interactions on Deuterium and their Flavor Sensitivity

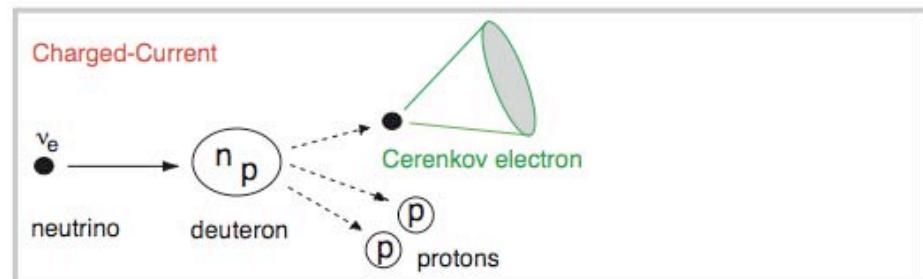


Charged-Current (CC)

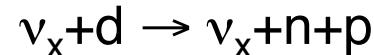


$$E_{\text{thresh}} = 1.4 \text{ MeV}$$

Measurement of energy spectrum

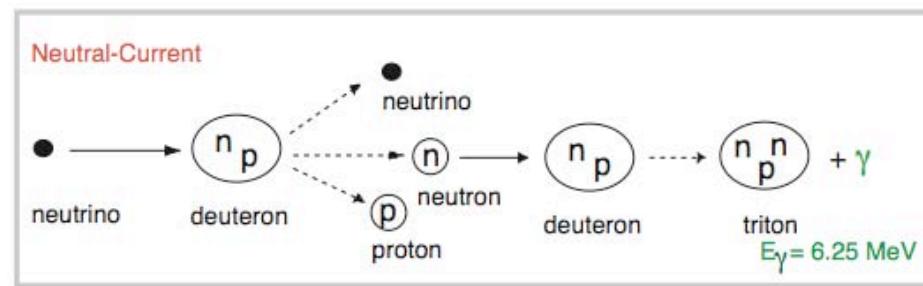


Neutral-Current (NC)

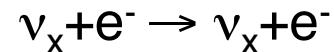


$$E_{\text{thresh}} = 2.2 \text{ MeV}$$

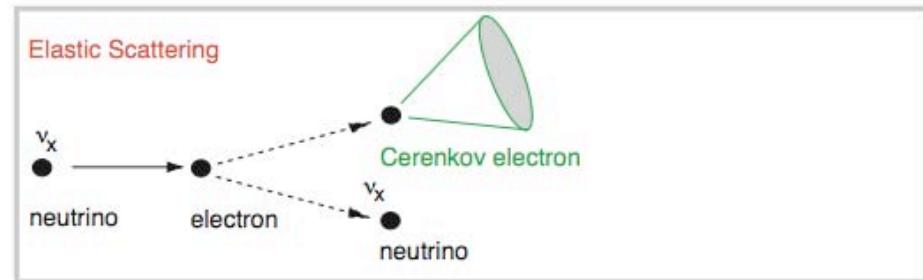
Measures total 8B flux from Sun



Elastic Scattering (ES)

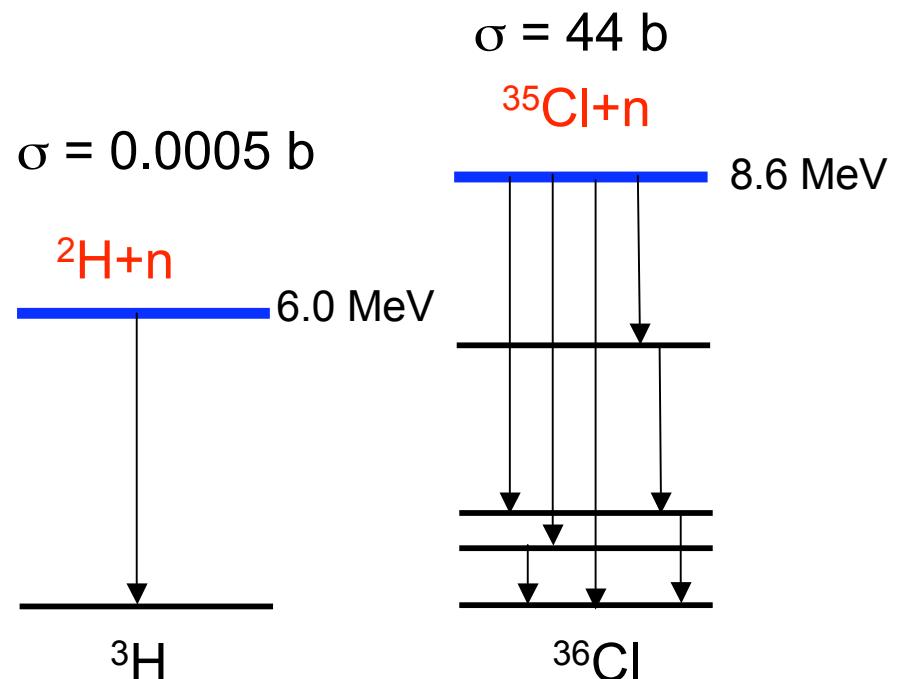
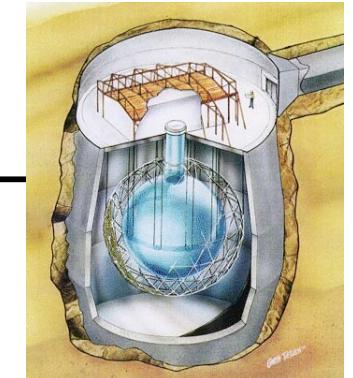
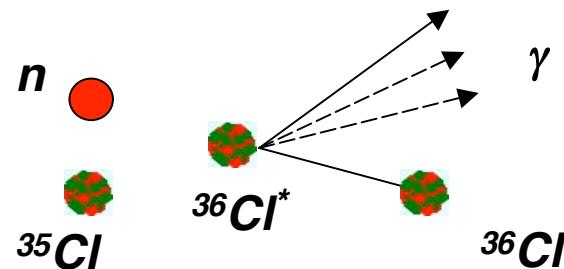
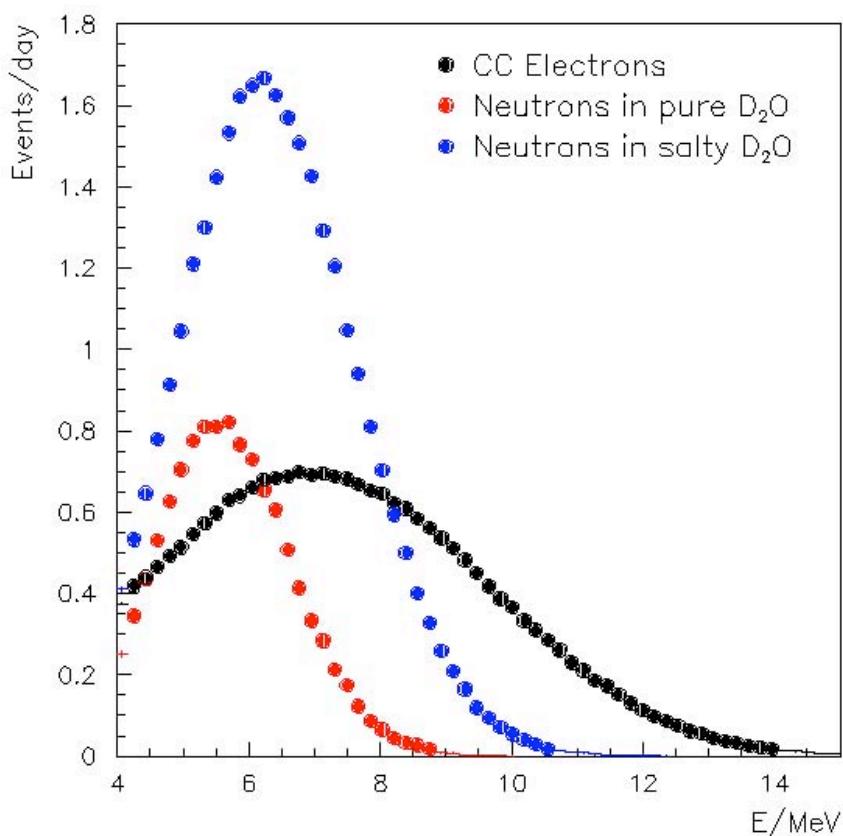


Strong directional sensitivity

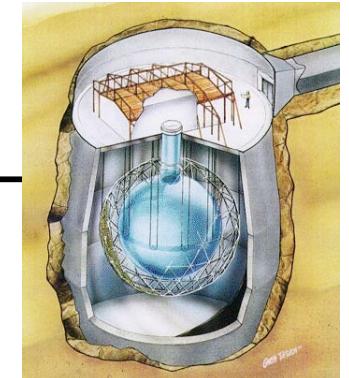
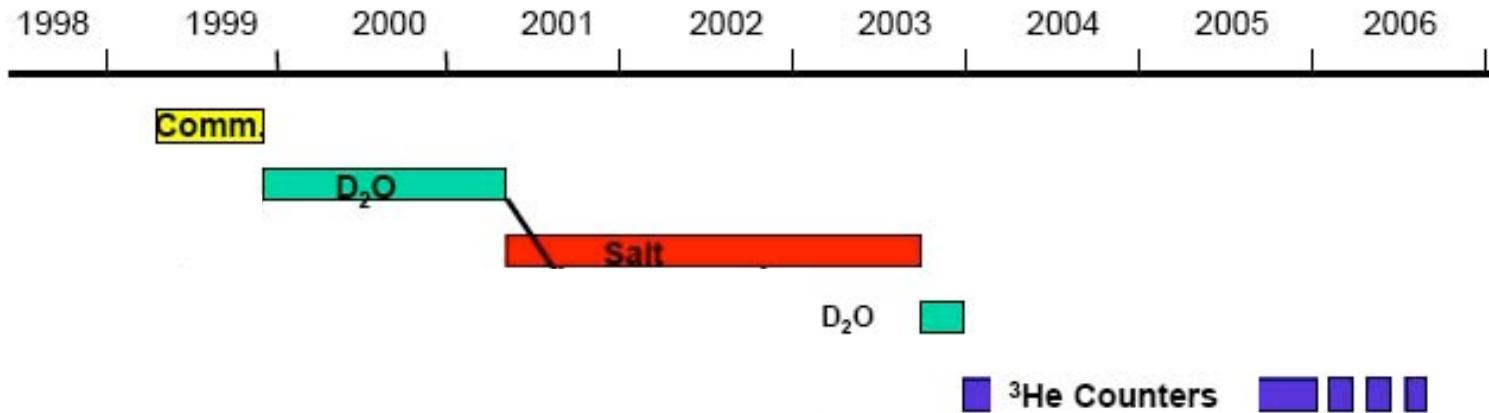


SNO - Enhanced Neutron Detection with NaCl

- Higher capture cross section
- Higher energy release
- Many gammas



SNO Run Sequence



I. Pure D₂O

CC, ES, NC
 $n+d \rightarrow t + \gamma \dots$ ($E\gamma = 6.25 \text{ MeV}$, $\varepsilon_n \sim 24\%$)

II. D₂O+NaCl

(added salt)

CC, ES, *enhanced* NC
 $n+^{35}\text{Cl} \rightarrow ^{36}\text{Cl} + \sum \gamma$
($E_{\sum \gamma} = 8.6 \text{ MeV}$, $\varepsilon_n \sim 45\%$ above threshold)

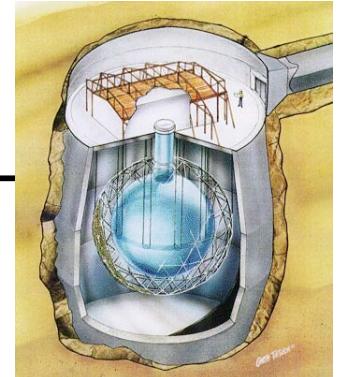
III. D₂O+NCDs

(³He proportional counters)

Event-by-event separation of NC and CC, ES
 $n+^3\text{He} \rightarrow p+t$ ($\varepsilon_n \sim 37\%$)

Looking for Unexpected Neutrino Flavors

Comparing total flux of solar ${}^8\text{B}$ neutrinos vs pure ν_e flux



CC/NC ratio is a direct signature
for flavor transitions

$$\frac{[CC]}{[NC]} = \frac{[\nu_e]}{[\nu_e + \nu_\mu + \nu_\tau]}$$

CC/ES could also show
significant effects

$$\frac{[CC]}{[ES]} = \frac{[\nu_e]}{[\nu_e + 0.15(\nu_\mu + \nu_\tau)]}$$



Smoking Gun for Neutrino Flavor Transformation
and Physics Beyond the Standard Model

Testing the Hypothesis of Neutrino Oscillations

Comparing the solar ν flux at Day and Night

Certain ν oscillation models
predict ν regeneration in Earth

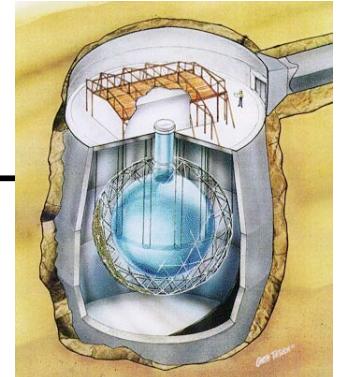
$$\frac{[CC]_{DAY}}{[CC]_{NIGHT}} = \frac{[\nu_e]_{DAY}}{[\nu_e]_{NIGHT}} \neq 1$$

$$\frac{[NC]_{DAY}}{[NC]_{NIGHT}} = \frac{[\nu_e + \nu_\mu + \nu_\tau]_{DAY}}{[\nu_e + \nu_\mu + \nu_\tau]_{NIGHT}} \neq 1$$



Solar Neutrino Physics with SNO

What can we learn from measuring the NC interaction rate (total active ${}^8\text{B}$ solar neutrino flux) at SNO?



- Total ${}^8\text{B}$ ν flux (NC) *versus* ν_e flux (CC)

$$\frac{[CC]}{[NC]} = \frac{[\nu_e]}{[\nu_e + \nu_\mu + \nu_\tau]} \quad \rightarrow \text{Test of neutrino flavor change}$$

- Total flux of solar ${}^8\text{B}$ neutrinos

\rightarrow Test of solar models

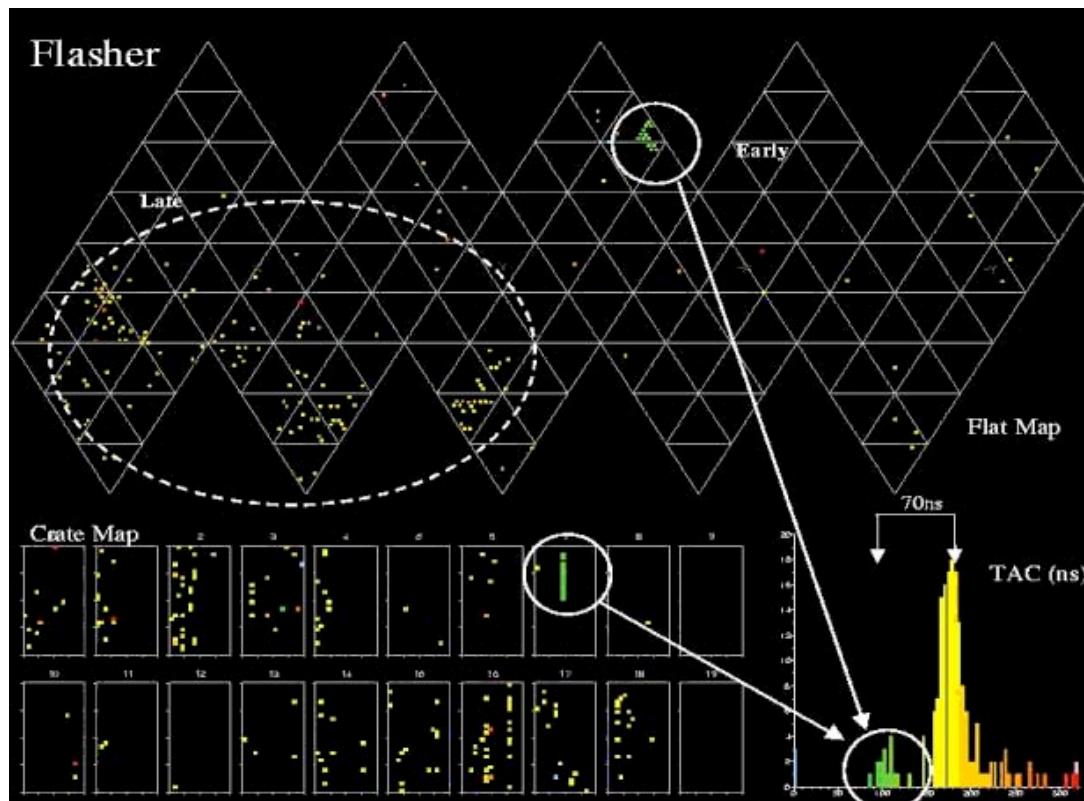
- Diurnal time dependence

\rightarrow Test of neutrino oscillations

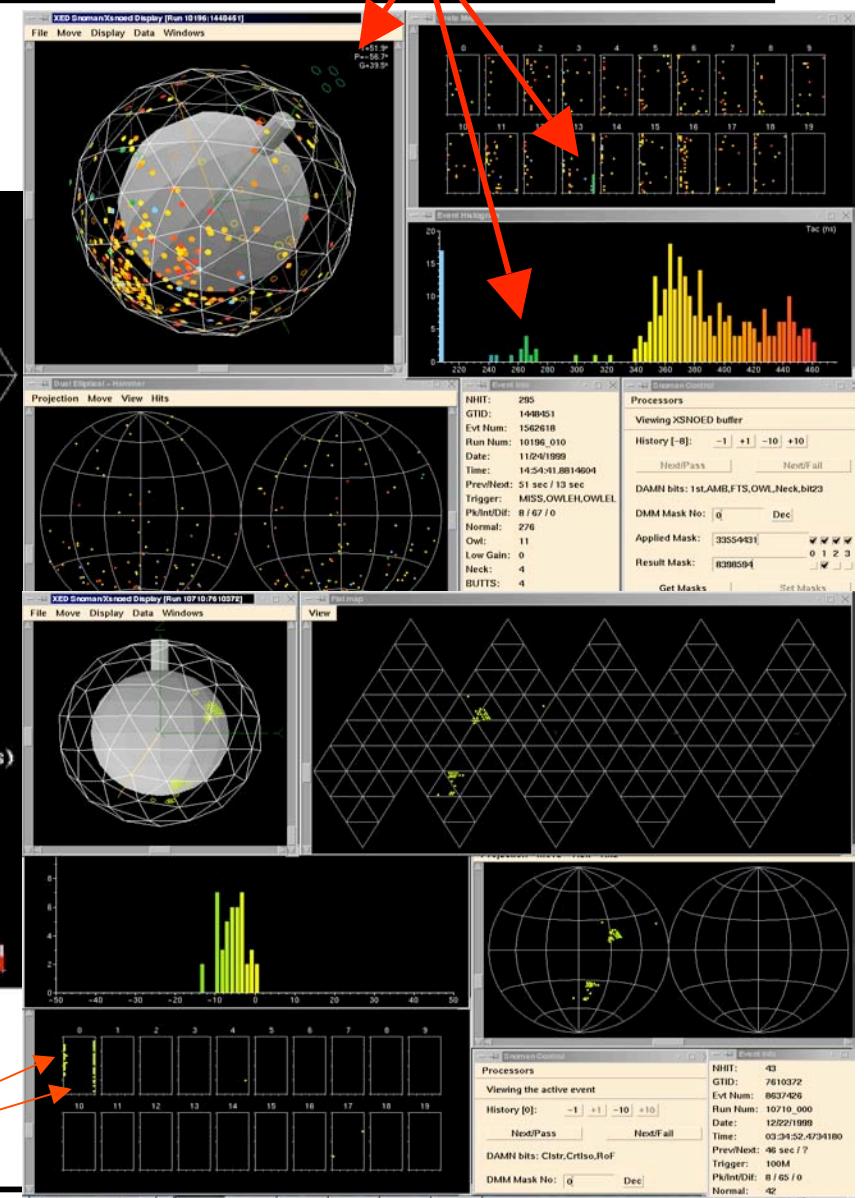
- Distortions of neutrino energy spectrum

\rightarrow Test of neutrino oscillations

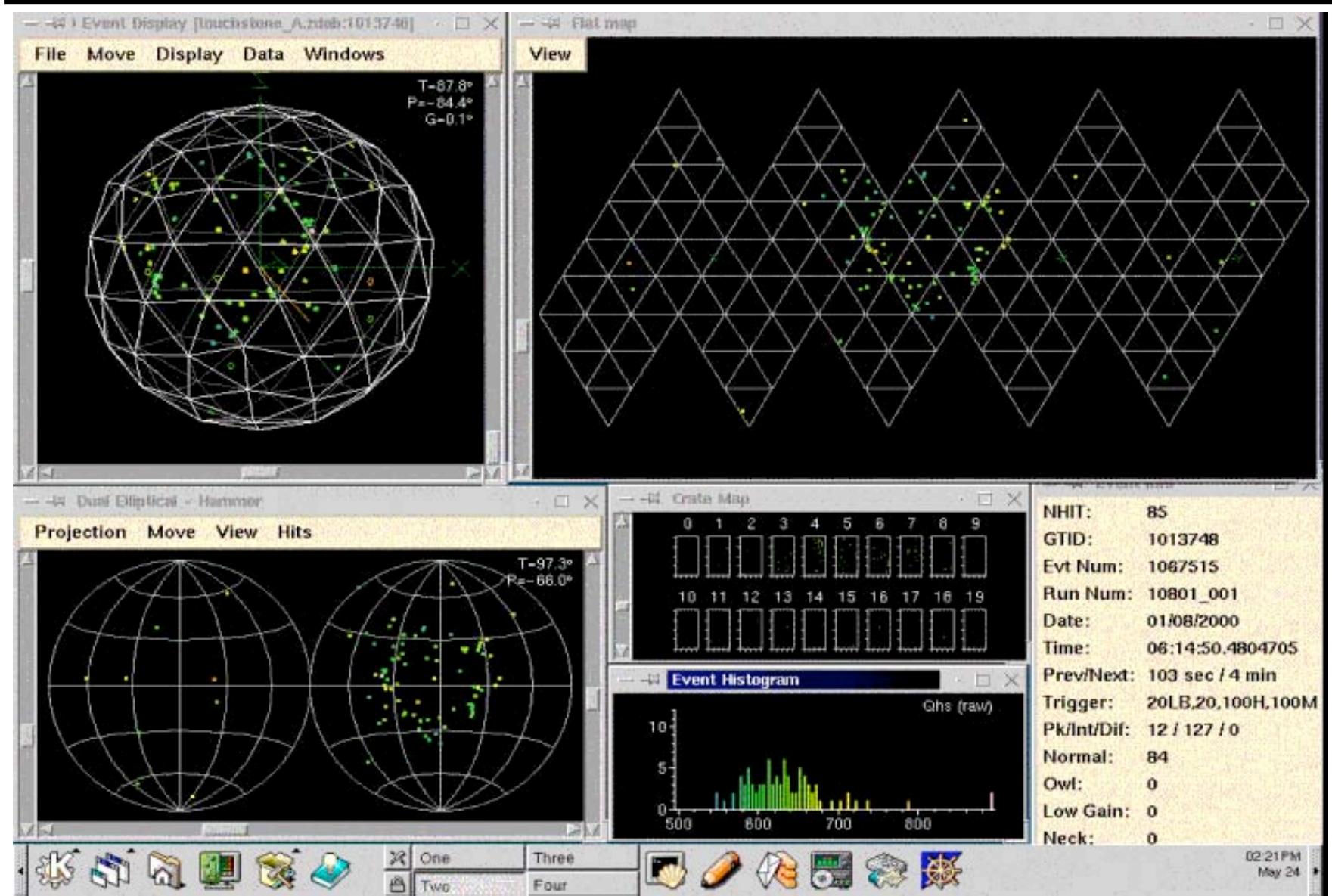
Instrumental Backgrounds



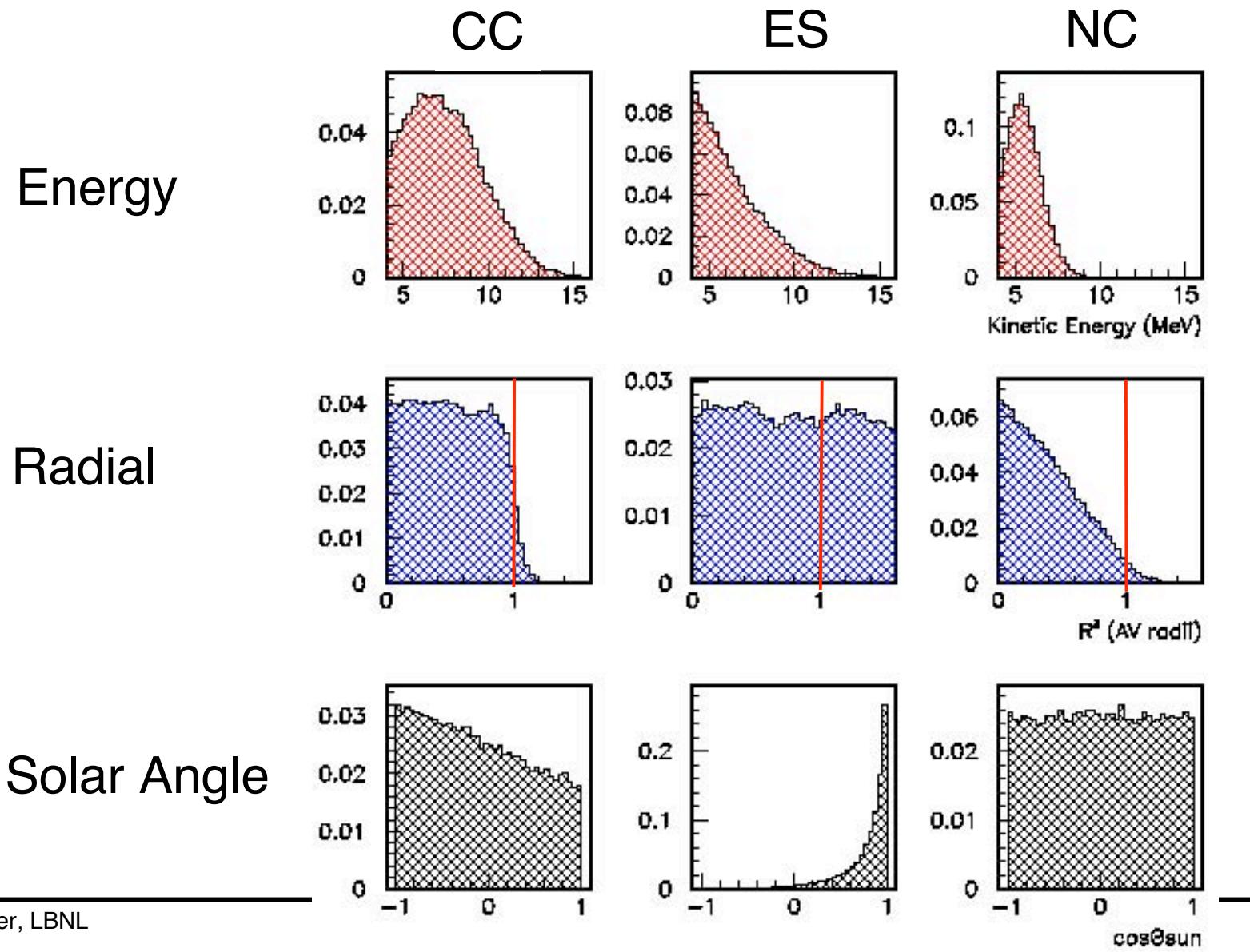
Electronic Pickup



Candidate Neutrino Event



Statistical Separation of Data Based on Characteristic Event Distributions



SNO Signal Extraction

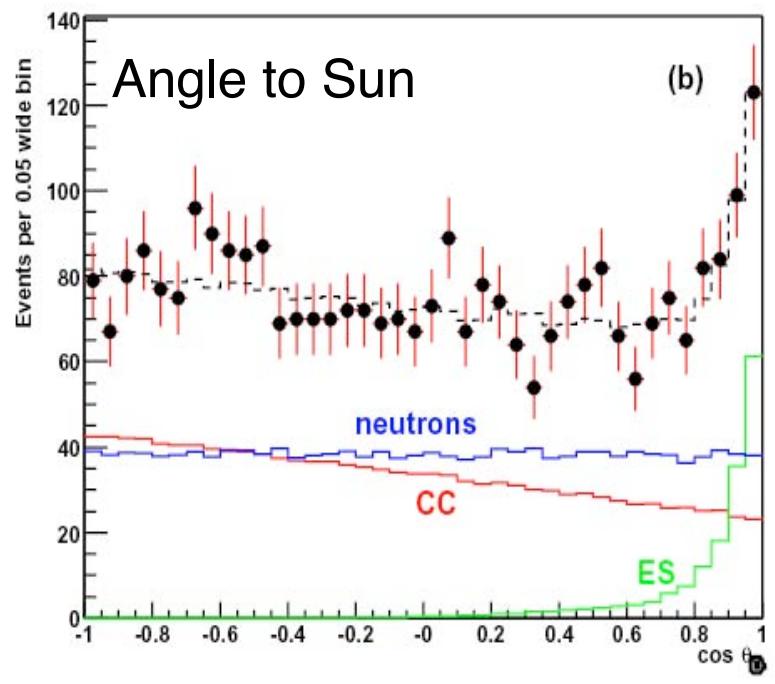
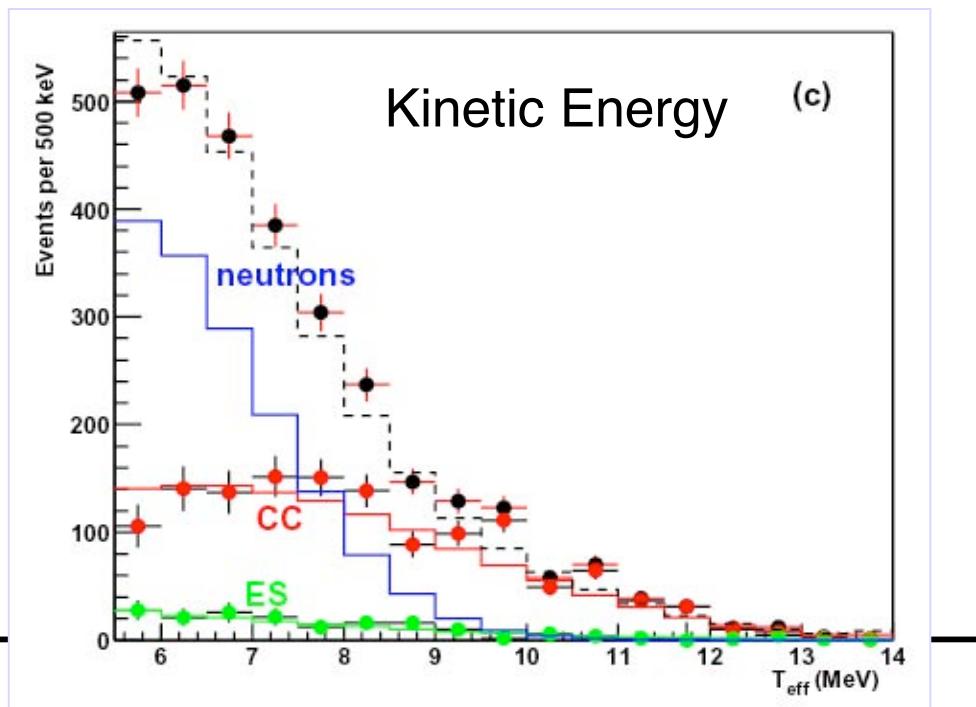
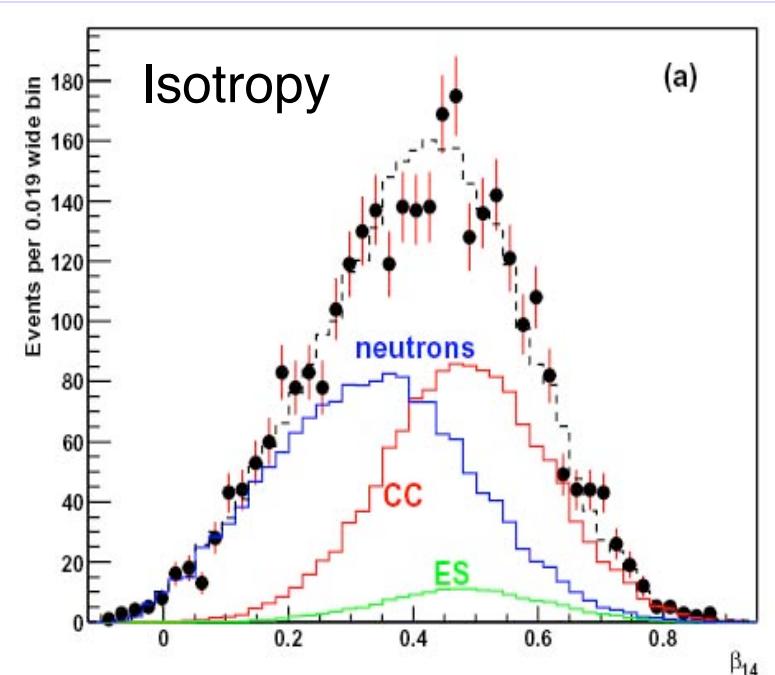
Data from July 26, 2001 to Oct. 10, 2002

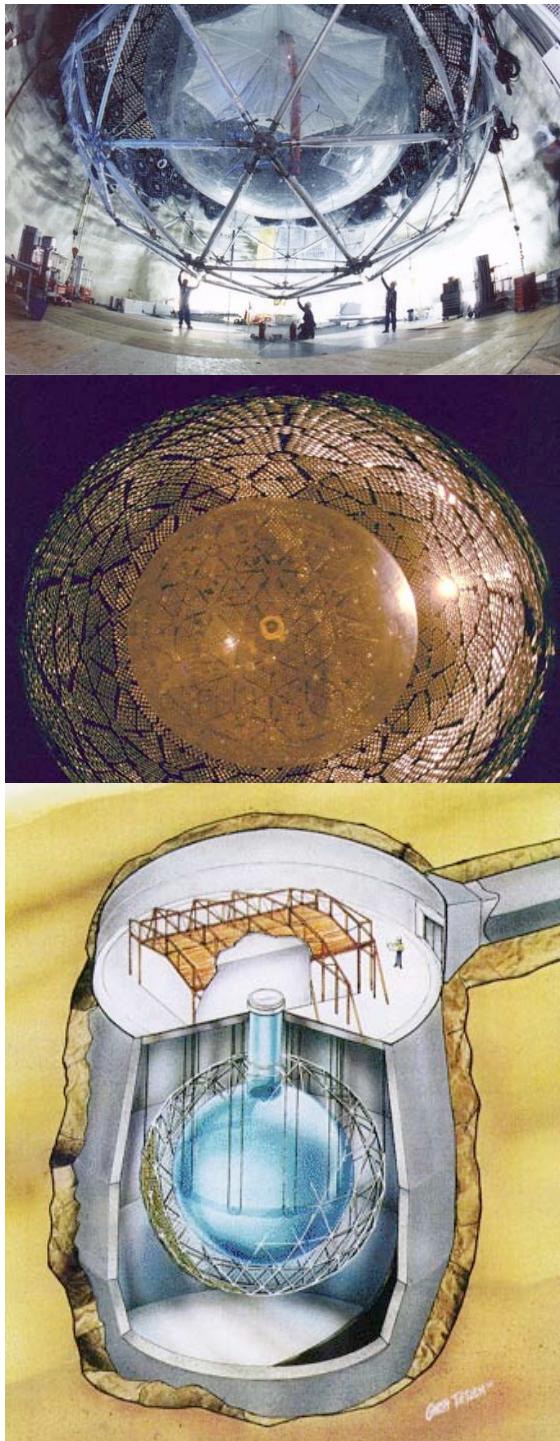
254.2 live days

Blind analysis performed

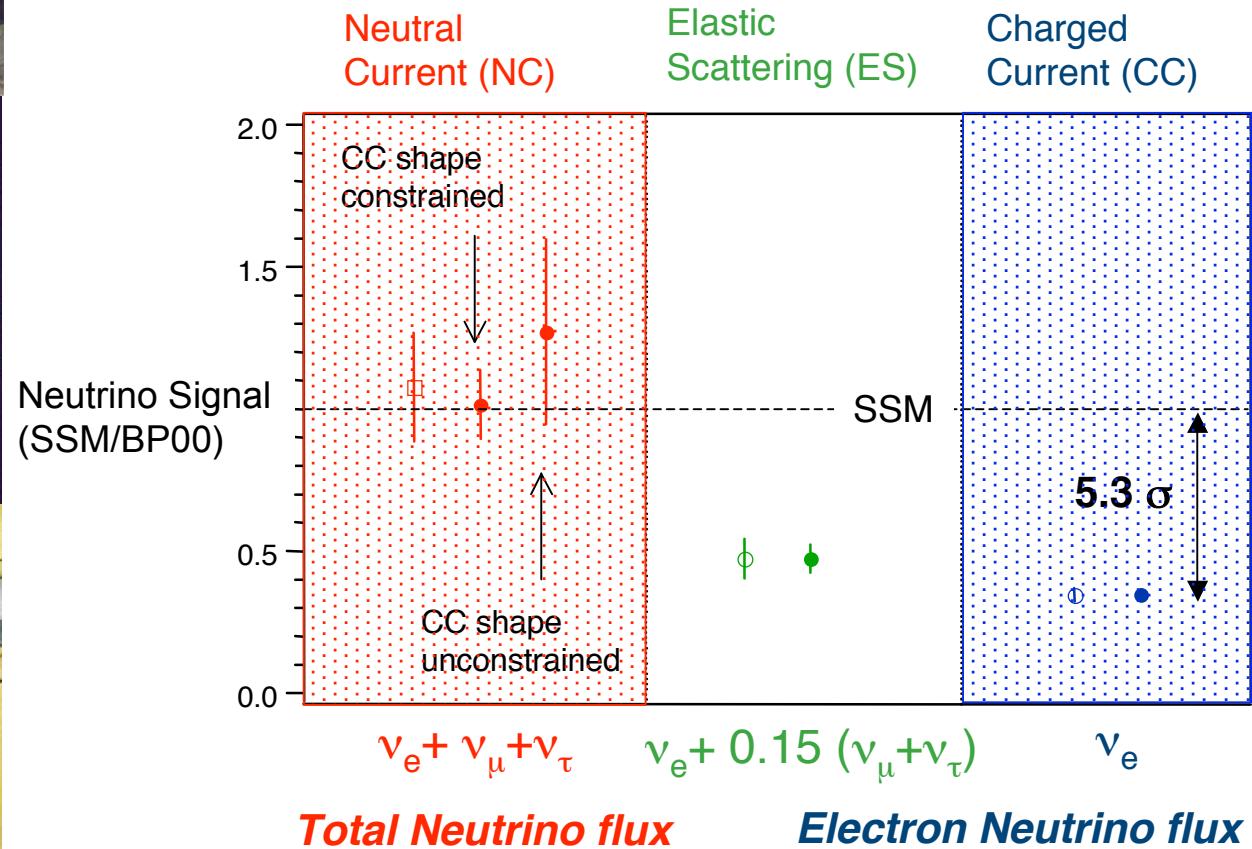
3055 candidate events:

1339.6 $^{+63.8}_{-61.5}$ CC
1344.2 $^{+69.8}_{-69.0}$ NC
170.3 $^{+23.9}_{-20.1}$ ES





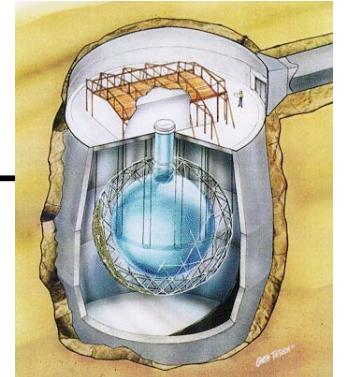
The Solution to the Solar Neutrino Problem: Neutrinos Change Flavor



2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$

Flavor Content of ${}^8\text{B}$ Solar Neutrino Flux

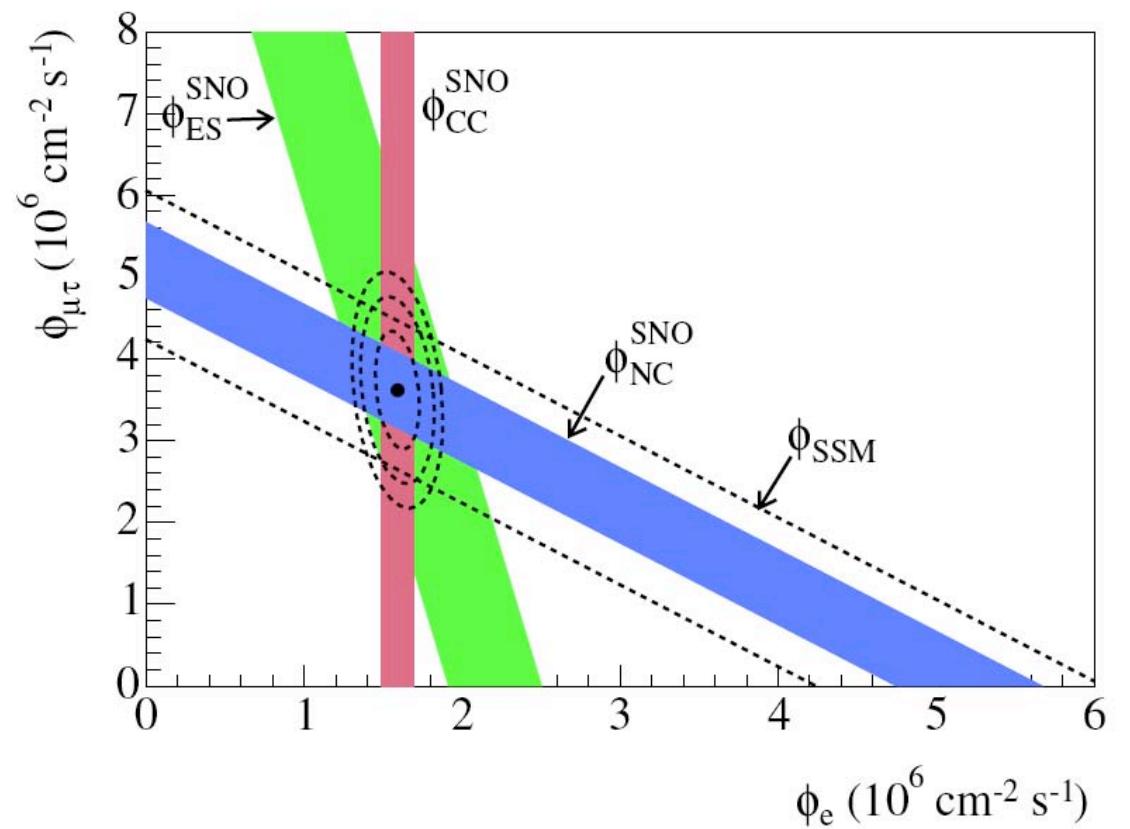
${}^8\text{B}$ Standard Solar Model (SSM01)	5.05	$\times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$
NC Salt Constrained	4.90 ± 0.38	$\times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$
NC Salt Unconstrained	5.21 ± 0.47	$\times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$



CC/NC Ratio

$0.306 \pm 0.026 \text{ (stat)} \pm 0.024 \text{ (sys)}$

Standard Solar Model
predictions for total ${}^8\text{B}$ flux in
excellent agreement!



Model-Independence of SNO ν_e/ν_x Flux Ratio

Is the SNO result model-independent?

1. ~~What about solar models?~~ SNO makes direct comparison of ν_e and ν_x

2. What about neutrino cross-sections?

In EFT weak axial two-body current $L_{1,A}$ is dominant uncertainty of low-energy weak interaction deuteron breakup process

Use $R_{NC} = \Phi_{\nu_x} \hat{\sigma}_{NC}(L_{1,A})$ to determine $\Phi_{\nu_x} = (6.4 \pm 1.4 \pm 0.6) 10^6 \text{ cm}^{-2} \text{ s}^{-1}$
 $R_{CC} = \Phi_{\nu_x} \hat{\sigma}_{CC}(L_{1,A}) \int dE \rho P_{\nu_e/\nu_x}$ $L_{1,A} = 4.0 \pm 4.7 \pm 4.5 \text{ fm}^3$
 $R_{ES} = R_{ES}(L_{1,A})$ $\nu_e/\nu_x \text{ ratio}$

Solar neutrino interaction rates R^{SNO}_{CC} , R^{SNO}_{NC} , R^{SK}_{ES} self-calibrate cross-section scaling!

Chen, KMH, Robertson, Phys.Rev.C67:025801,2003

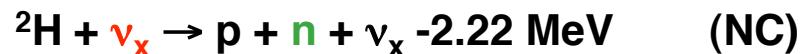
SNO Phase III - Neutral Current Detection via ${}^3\text{He}(\text{n},\text{p}){}^3\text{H}$

Array of ${}^3\text{He}$ counters

50 Strings on 1-m grid

450 m total active length

Detection Principle

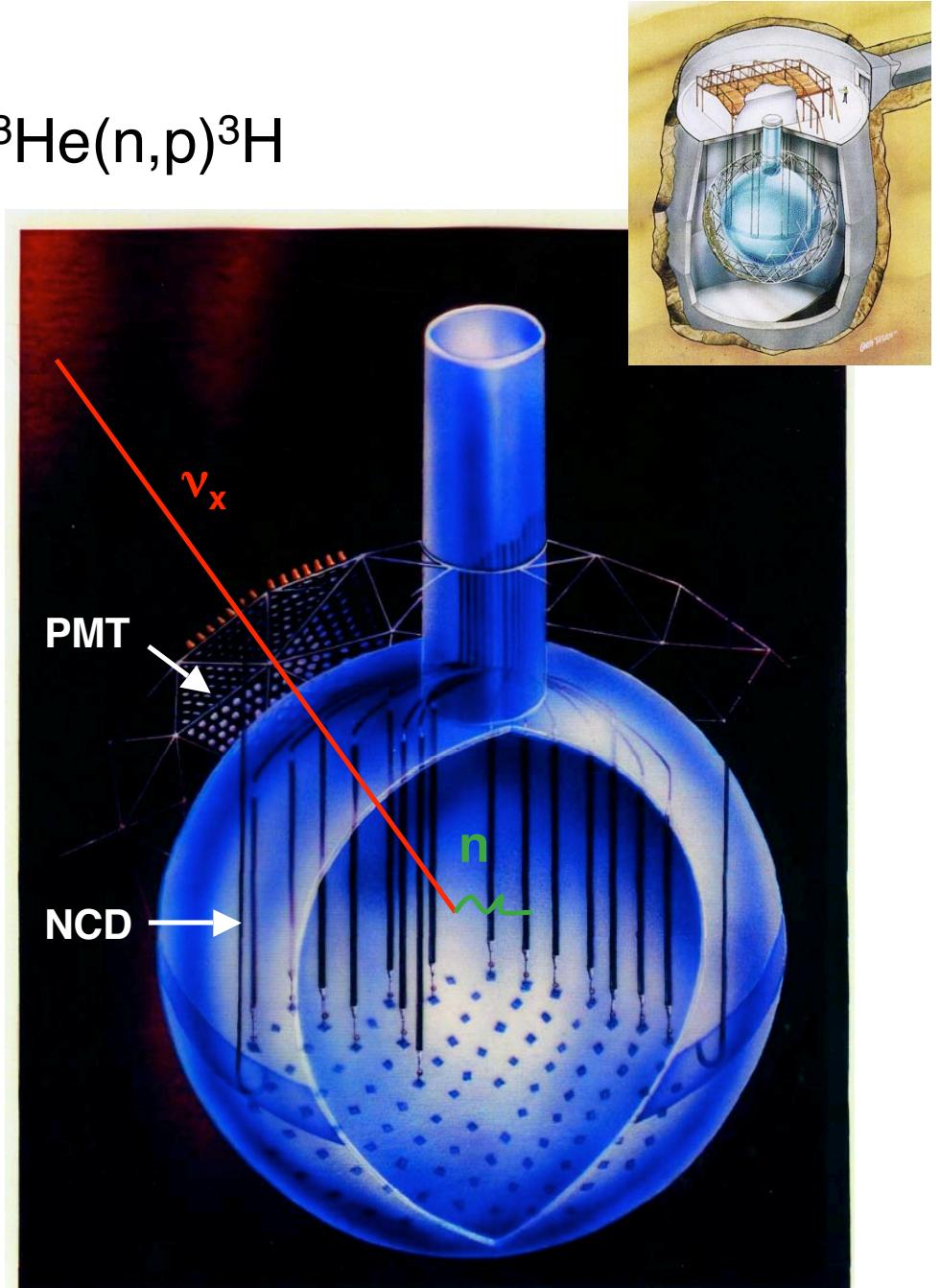


Physics Motivation

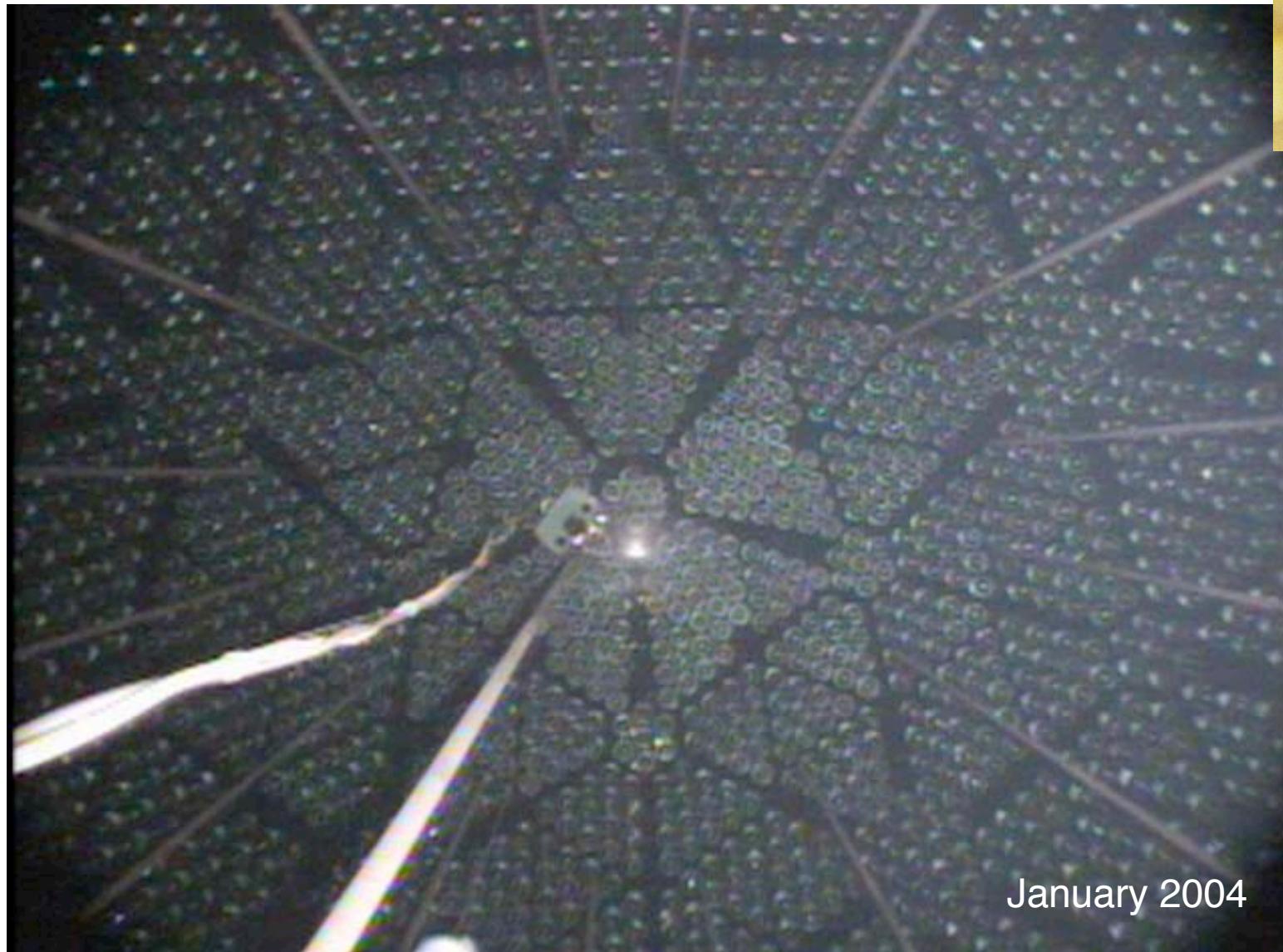
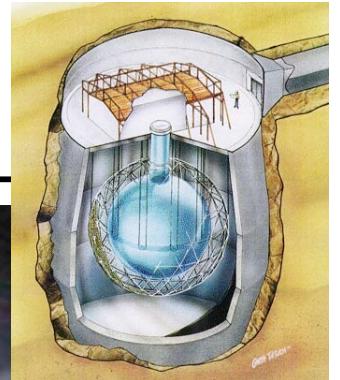
Event-by-event separation. Measure NC and CC in separate data streams.

Different systematic uncertainties than neutron capture on NaCl.

NCD array as active poison.



Installation of SNO Neutral Current Detectors



Beyond the Standard Model: Neutrino Mass & Mixing

Neutrino Flavor Transformation through Oscillations

If neutrinos have mass leptons can mix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstates are a mixture of mass eigenstates, and evolve with time or distance

$$\nu_e = U_{e1} e^{-iE_1 t} \nu_1 + U_{e2} e^{-iE_2 t} \nu_2 + U_{e3} e^{-iE_3 t} \nu_3$$

In 3- ν scheme with Dirac neutrinos: $U_{MNSP} = U_{\text{atm}} * U_{e3} * U_{\text{solar}}$ $\delta = \text{CP violating phase}$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric } \nu} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator } \nu} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu}$$

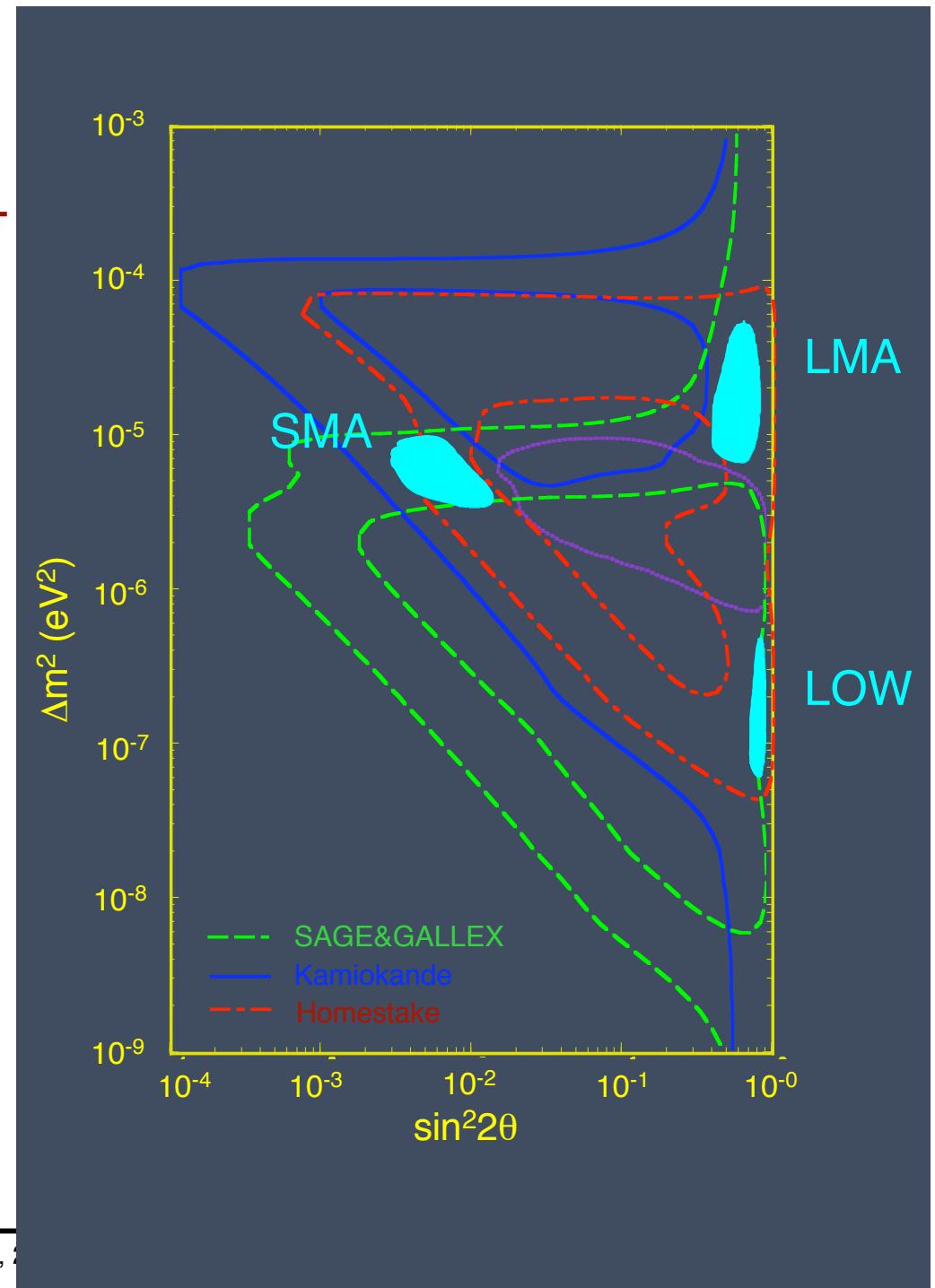
Oscillation Interpretation of Solar Neutrino Data

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

solar ν

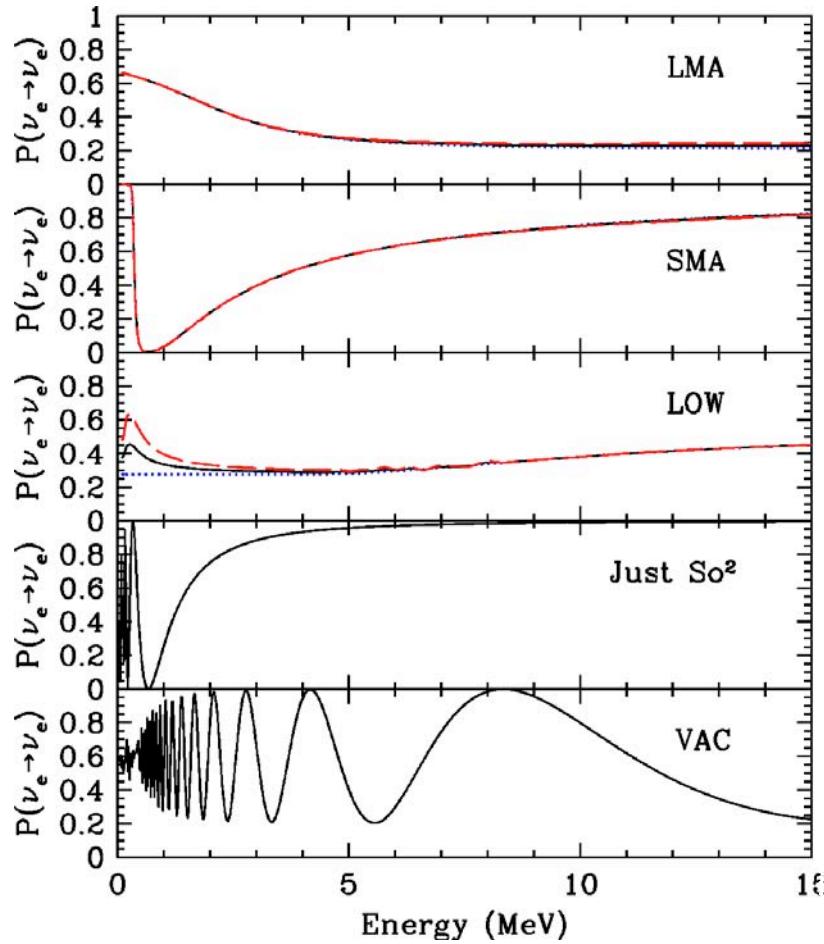
*Matter-enhanced oscillations (MSW):
Energy-dependent oscillation effect*

Gallium	GALLEX/GNO, SAGE
Chlorine	Homestake
Water	Super-Kamiokande



Solar Neutrino Survival Probabilities

Bahcall et al. hep-ph/0103179v3



$$\Delta m^2 (\text{eV}^2)$$

$$4.2 \times 10^{-5}$$

$$5.2 \times 10^{-6}$$

$$7.6 \times 10^{-8}$$

$$5.5 \times 10^{-12}$$

$$1.4 \times 10^{-10}$$

$$\tan^2 \theta$$

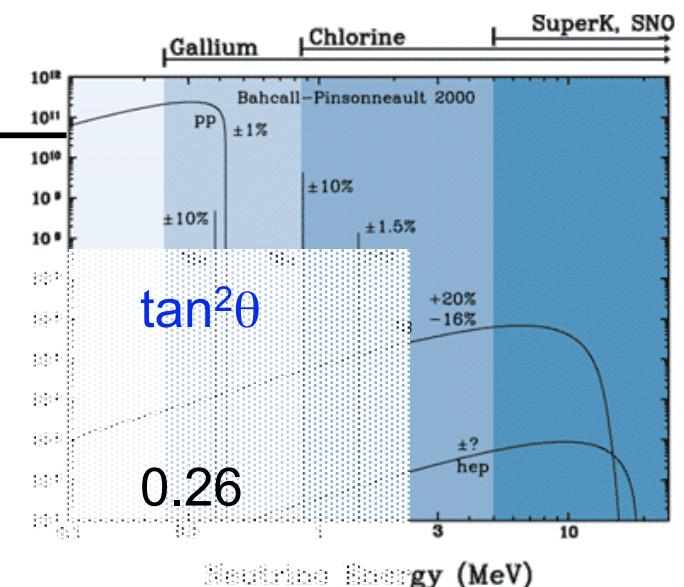
$$0.26$$

$$0.00052$$

$$0.72$$

$$1.0$$

$$0.38$$

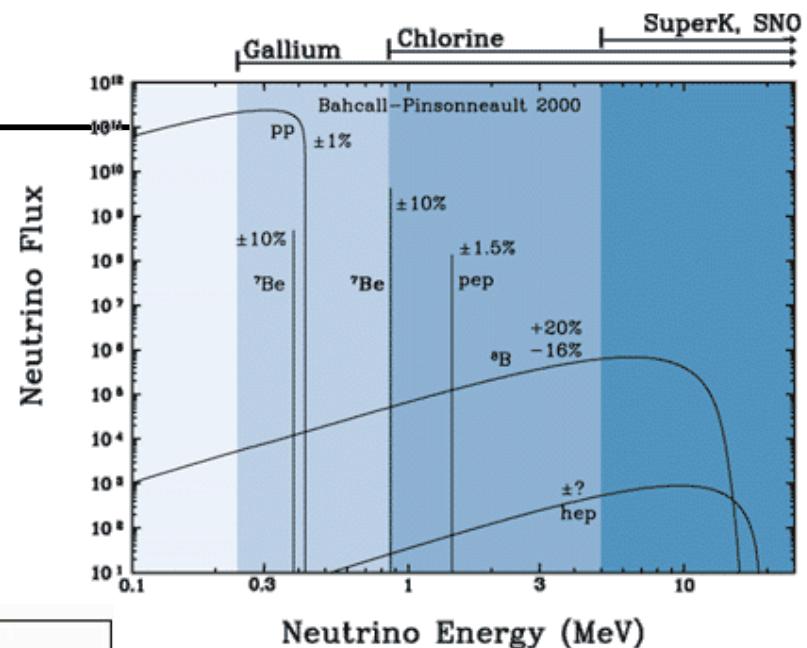
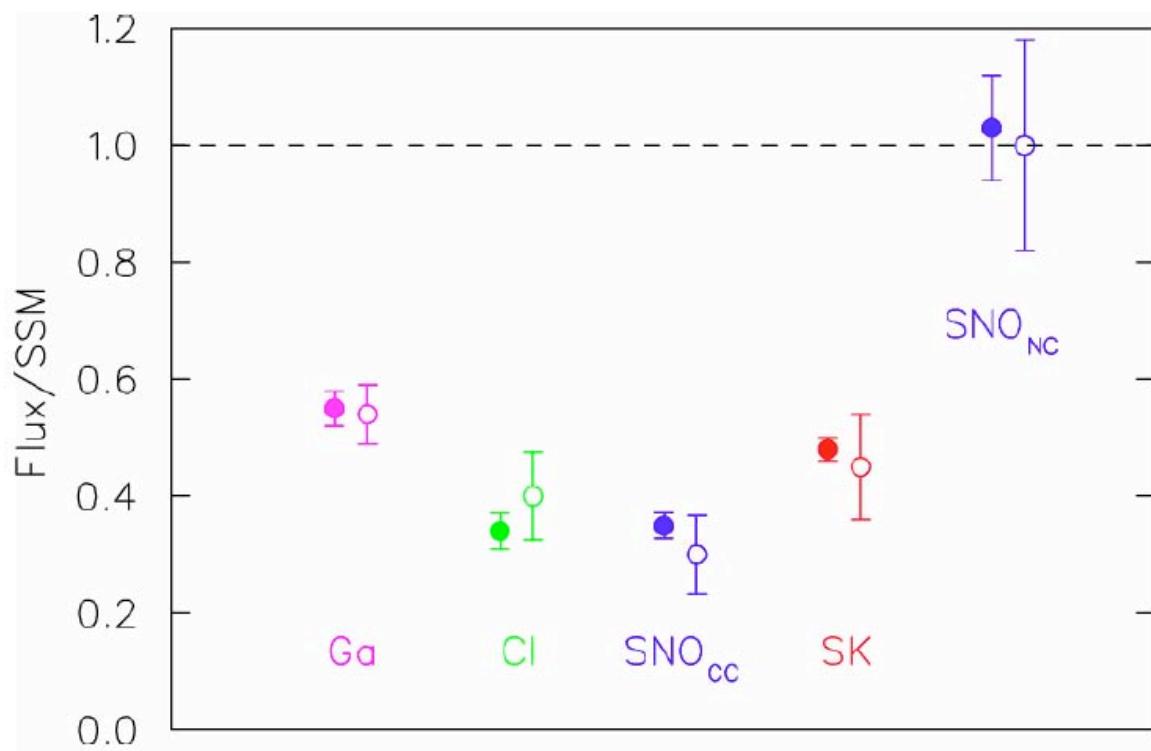


Solar Neutrino Measurements

Best Global Fits / Measured Rates

Open circles: combined best oscillation fit

Closed circles: experimental data



Ref: hep-ph/0402025

Neutrino Oscillation Experiments

Reactor and Beamstop Neutrinos

$$\nu_\mu \Rightarrow \nu_s \Rightarrow \nu_e$$

Atmospheric and Reactor Neutrinos

$$\nu_\mu \Rightarrow \nu_\tau$$

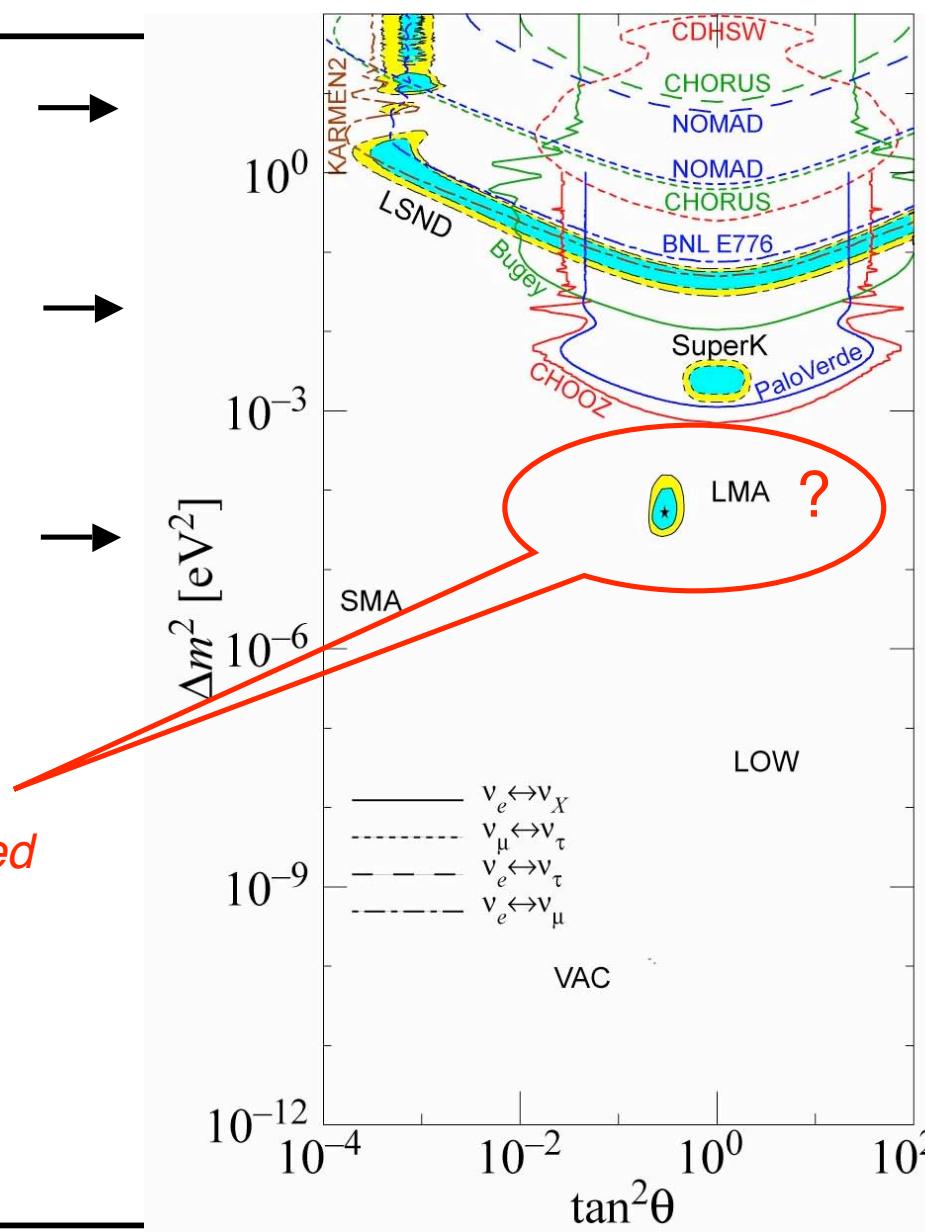
Solar and Reactor Neutrinos

$$\nu_e \Rightarrow \nu_{\mu,\tau}$$

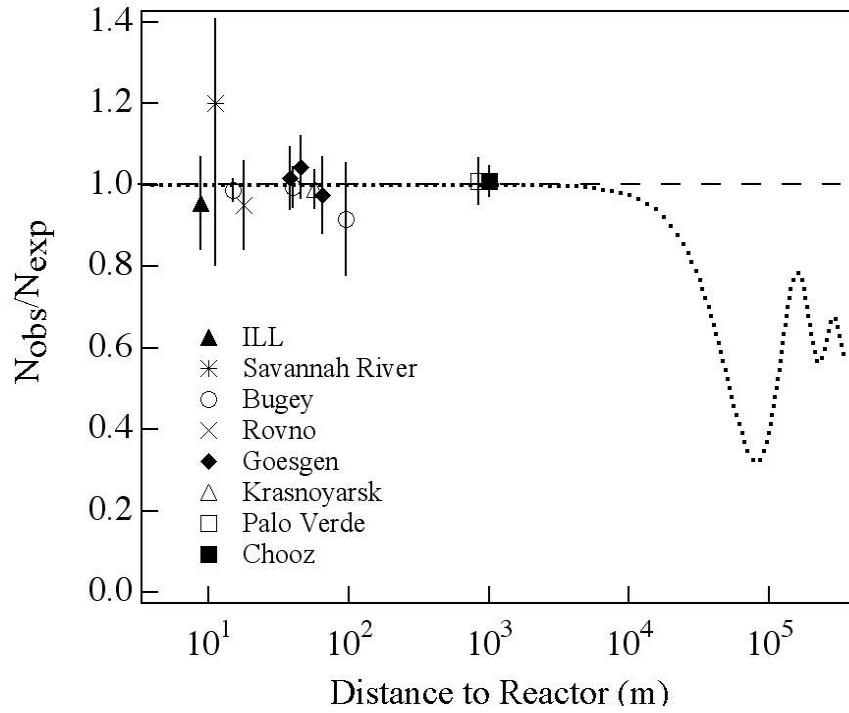
Large mixing favored

LMA solution can be tested
with reactor neutrinos

Status: Summer 2002



Search for Neutrino Oscillations with Reactor Neutrinos



Results from solar experiments suggest study of reactor neutrinos with a baseline of ~ 70 km

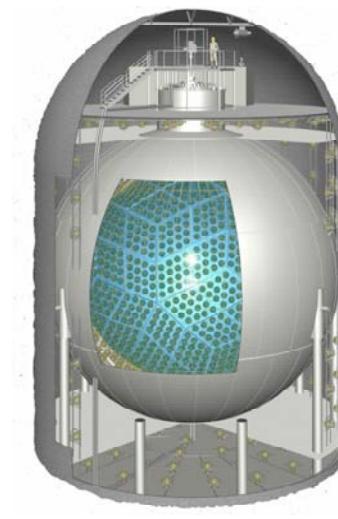
50 Years of Reactor Neutrino Physics

1953 First reactor neutrino experiment

1956 “*Detection of Free Antineutrino*”, F. Reines and C.L. Cowan

→ Nobel Prize in 1995

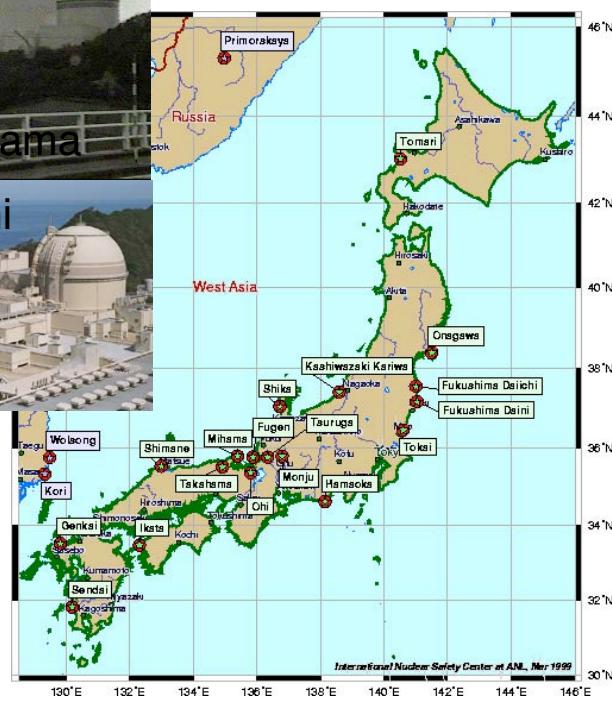
No signature of neutrino oscillations until 2002!



Japan

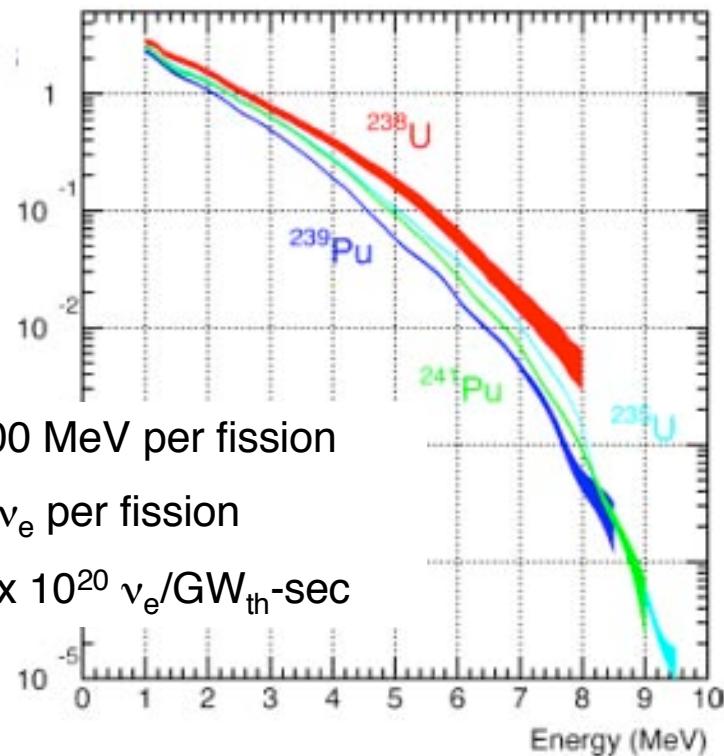
Reactor Antineutrinos

From Japanese Reactors



Spectrum from Principal Reactor Isotopes

neutrinos/MeV/fission

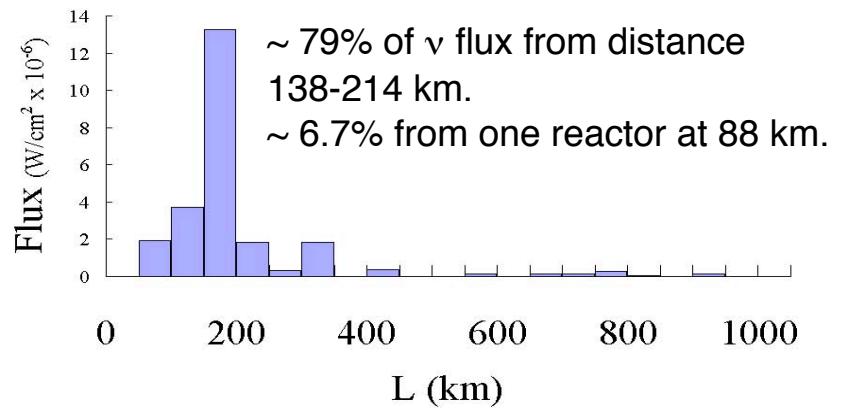


~ 200 MeV per fission

~ 6 ν_e per fission

~ $2 \times 10^{20} \nu_e/\text{GW}_{\text{th}}\text{-sec}$

Neutrino Flux at KamLAND



~ 79% of ν flux from distance

138-214 km.

~ 6.7% from one reactor at 88 km.

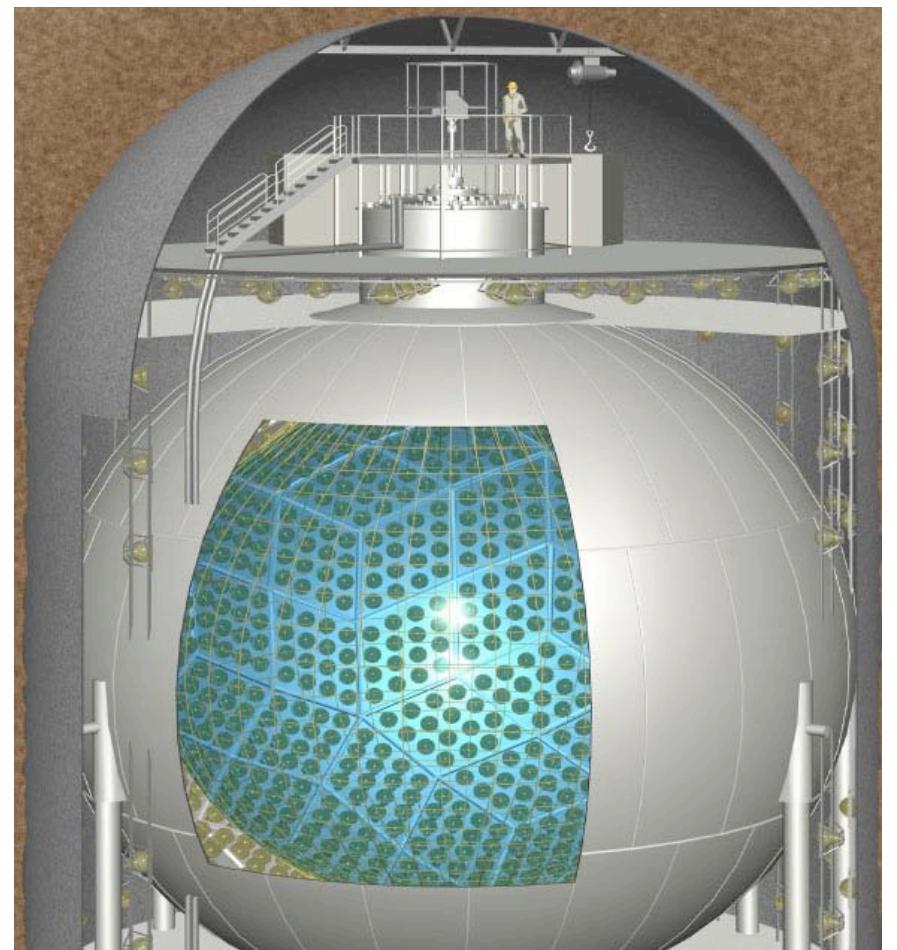
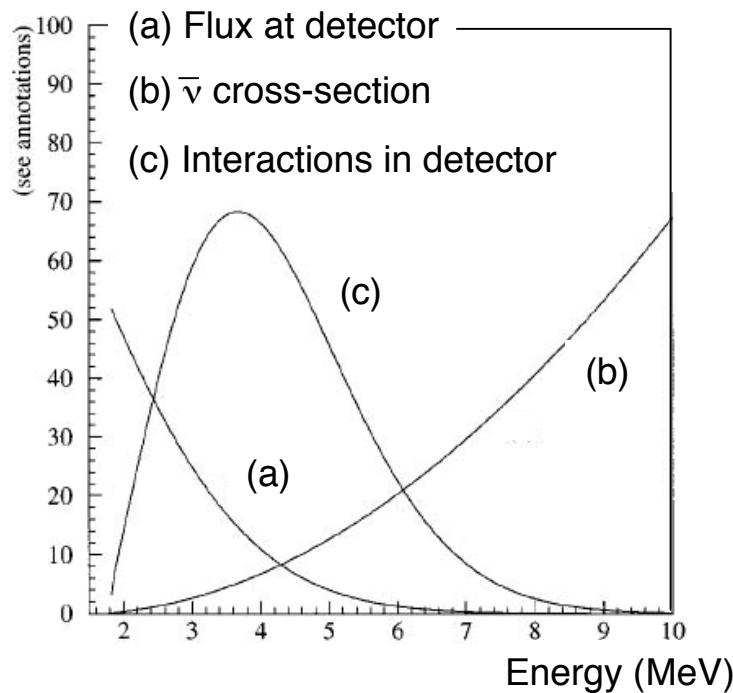
KamLAND - Kamioka Liquid Scintillator Antineutrino Detector

Uses reactor neutrinos to study $\bar{\nu}$ oscillation
with a baseline of $L \sim 140\text{-}210$ km

Coincidence Signal: $\bar{\nu}_e + p \rightarrow e^+ + n$

Prompt e^+ annihilation

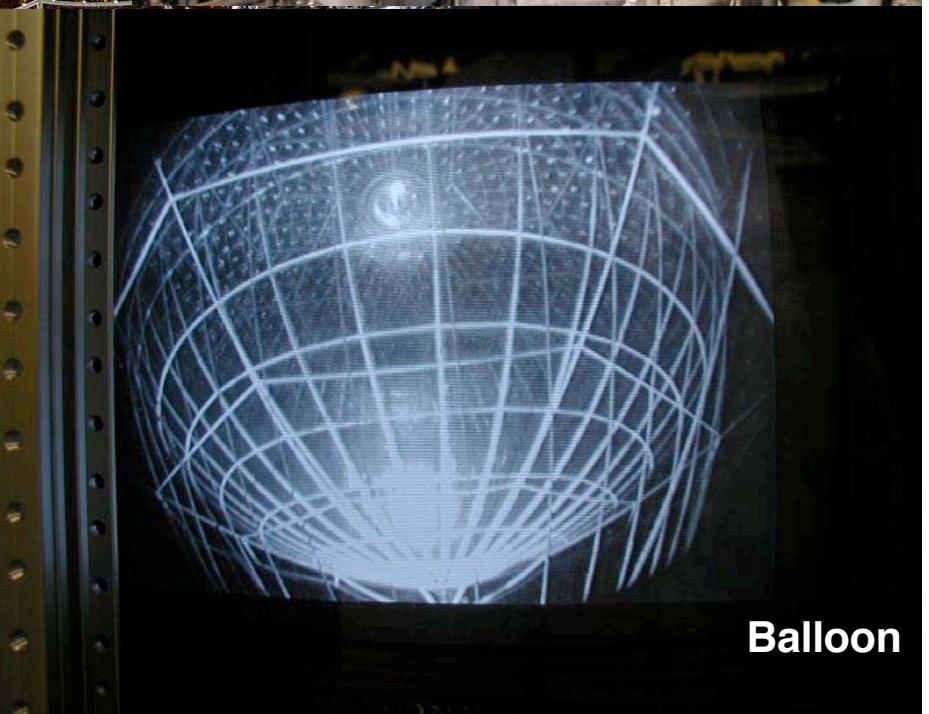
Delayed n capture, $\sim 190\ \mu\text{s}$ capture time



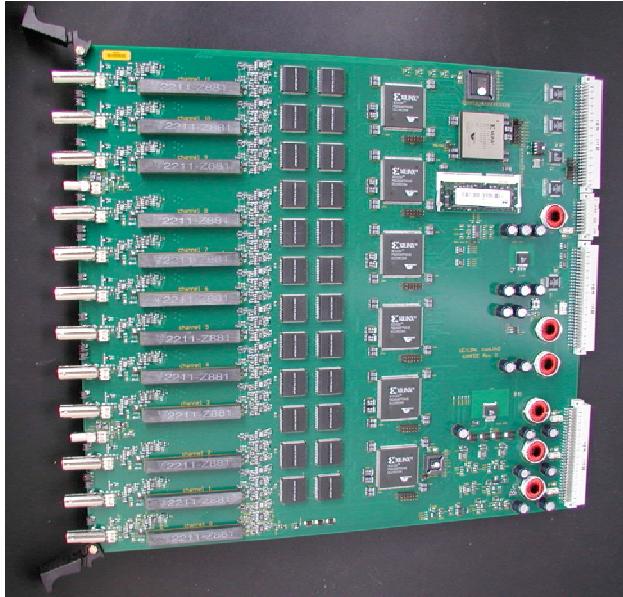
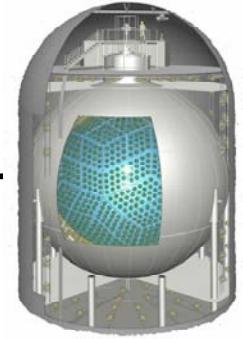
KamLAND studies the disappearance of $\bar{\nu}_e$ and measures

- interaction rate
- energy spectrum

KamLAND

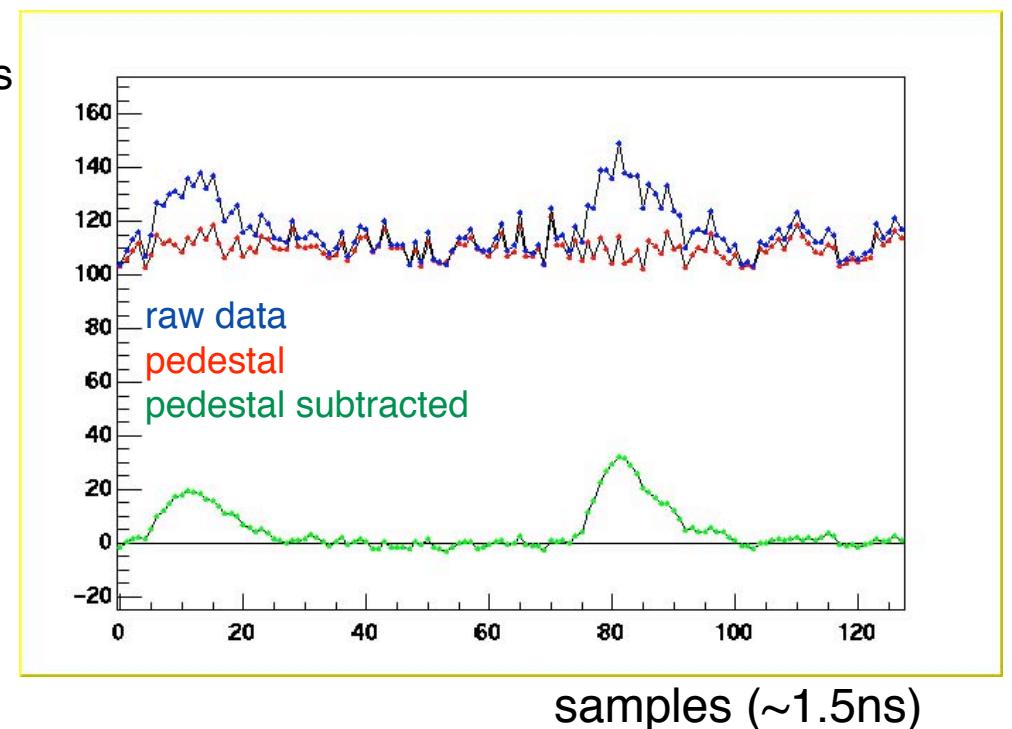


Front End Electronics

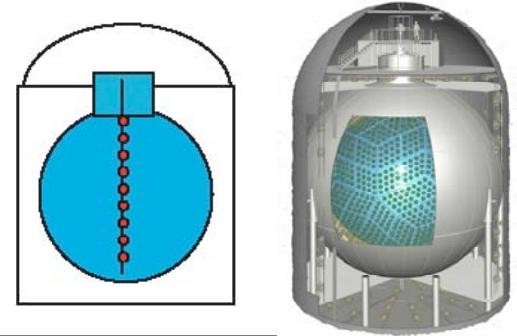


Waveforms are recorded using **Analogue Transient Waveform Digitizers (ATWDs)**, allowing multi p.e. resolution

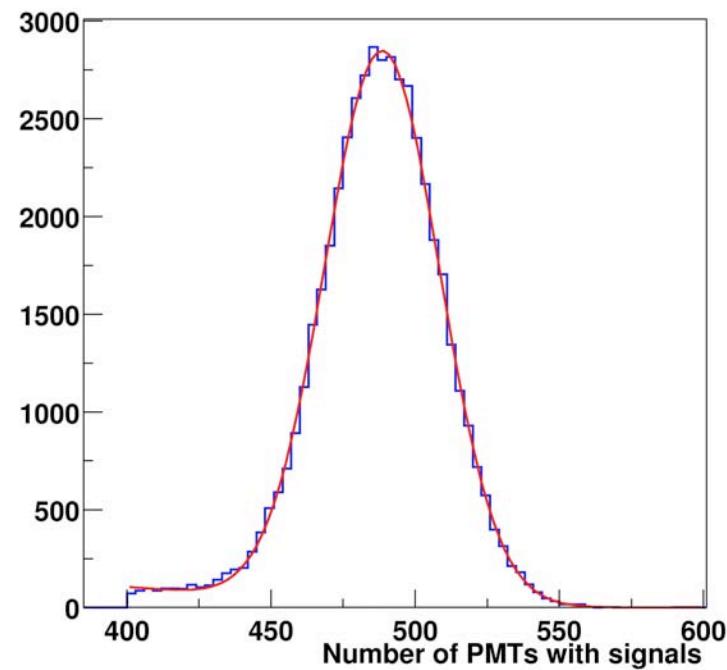
- The ATWDs are self launching with a threshold $\sim 1/3$ p.e.
- Each PMT is connected to 2 ATWDs, reducing deadtime
- Each ATWD has 3 gains (20, 4, 0.5), allowing a dynamic range of $\sim 1\text{mV}$ - $\sim 1\text{V}$



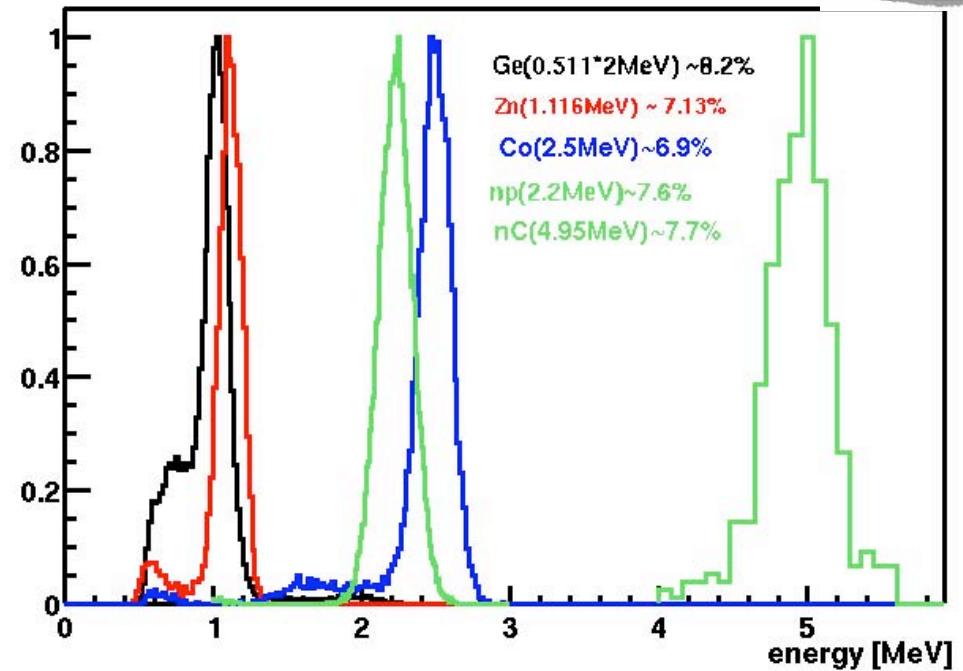
Detector Energy Scale and Response



Co60 At Center Of Detector



^{60}Co : 1.173+1.333 MeV



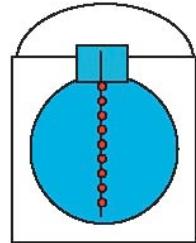
$\Delta E_{\text{syst}} = 1.91\% \text{ at } 2.6 \text{ MeV} \rightarrow 2.13 \% \text{ for } \bar{\nu}_e$

$\Delta E/E \sim 7.5\% / \sqrt{E}$

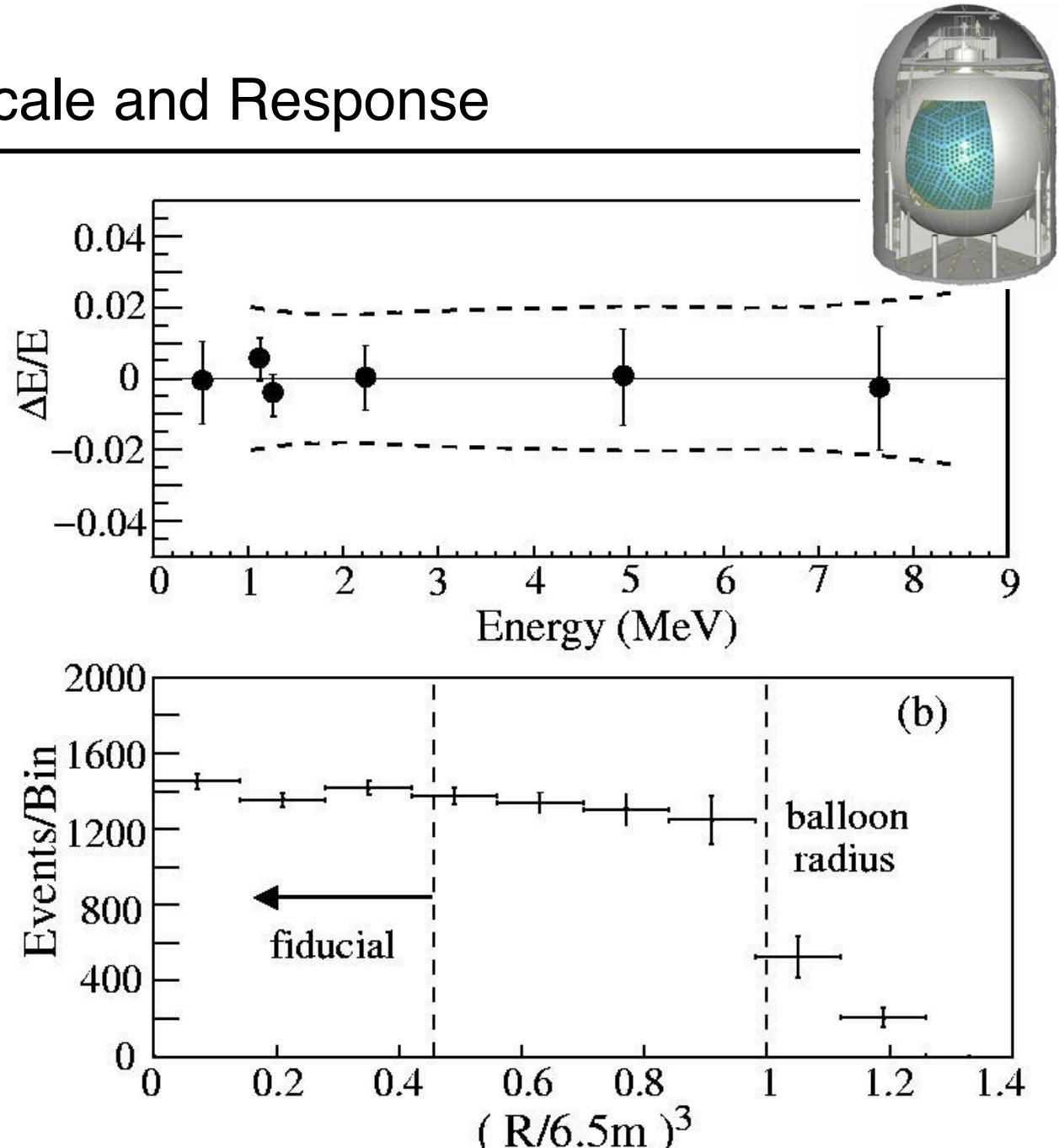
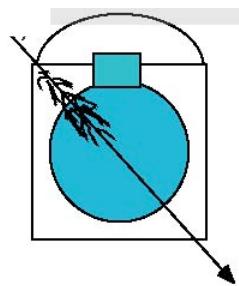
Light yield $\sim 300\text{p.e./MeV}$

Energy varies by < 0.5% within 10 m.

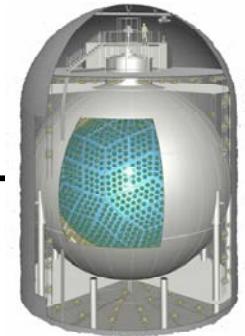
Detector Energy Scale and Response



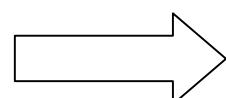
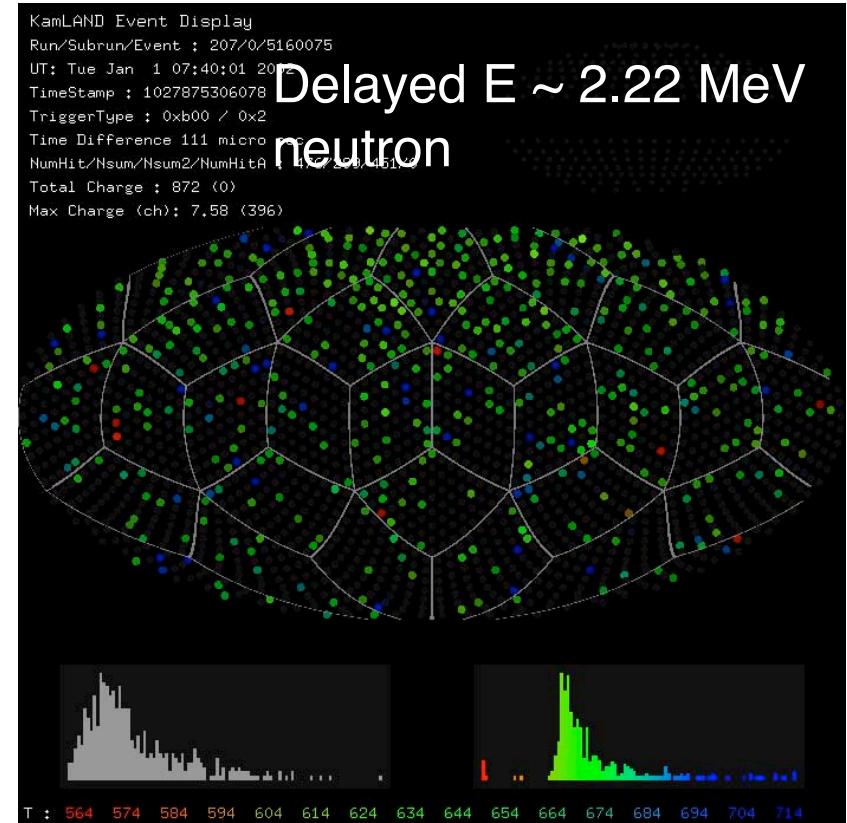
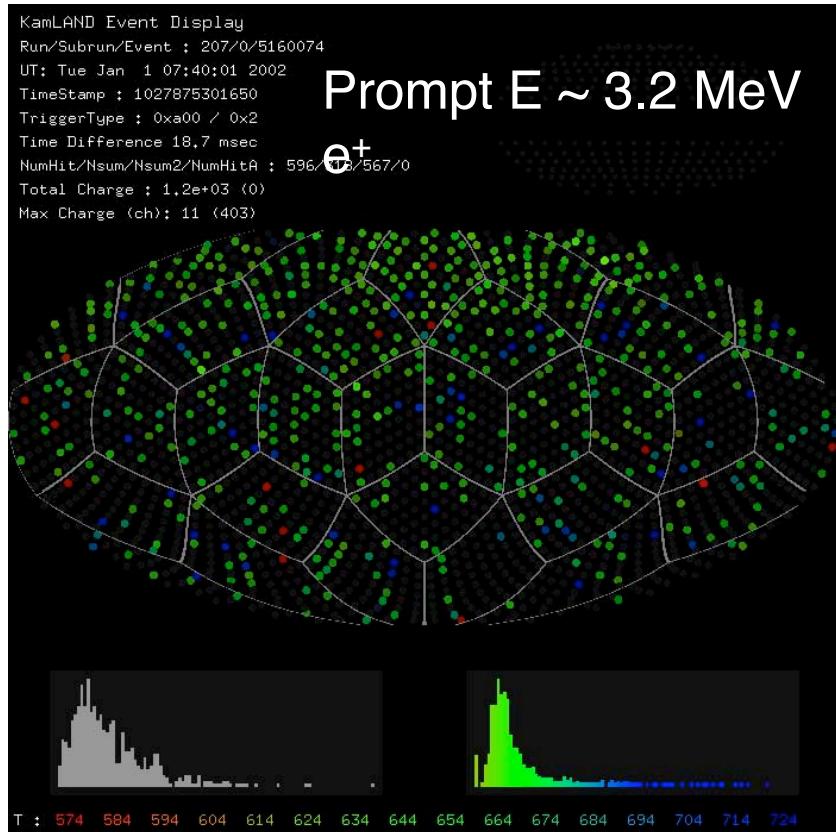
$$\Delta E / E = 7.5\% / \sqrt{E}$$



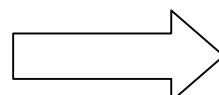
Conicidence Event Signal



Candidate Antineutrino Event

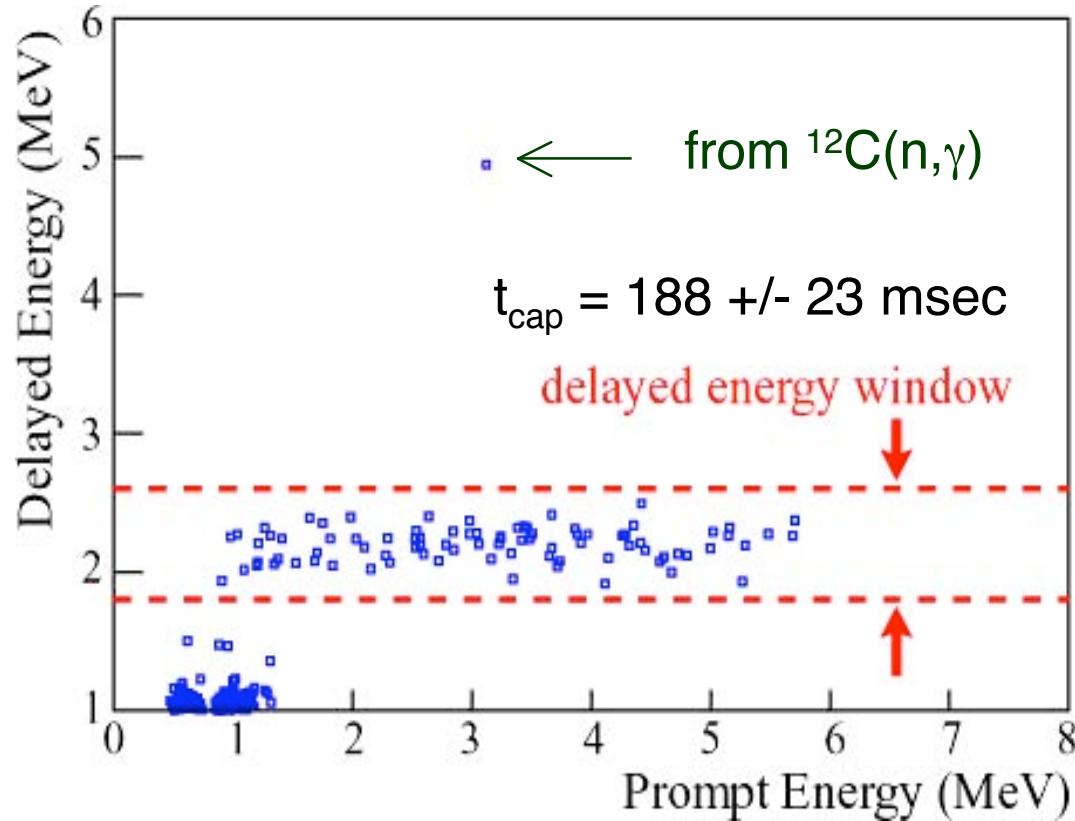


$\Delta t \sim 110 \mu s$
 $\Delta R \sim 0.35 \text{ m}$

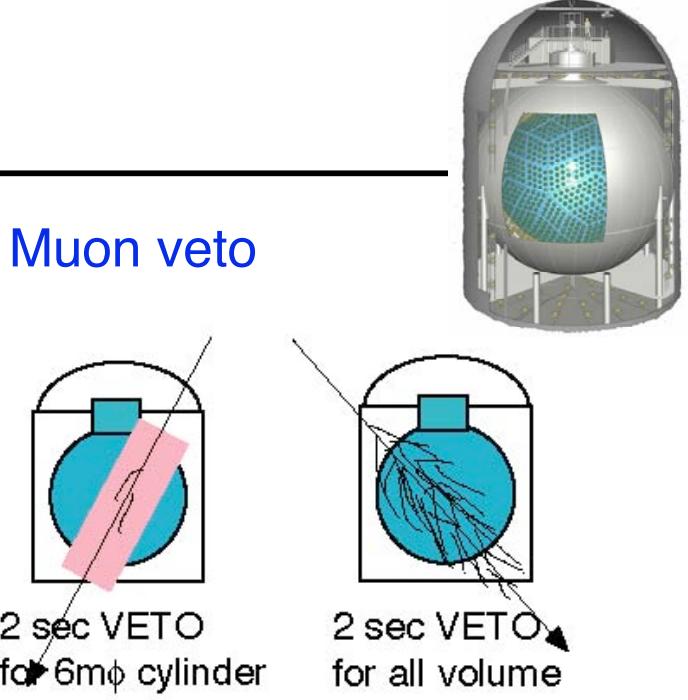


Event Selection

Delayed Energy Window



Muon veto



Vertex and Time Correlation

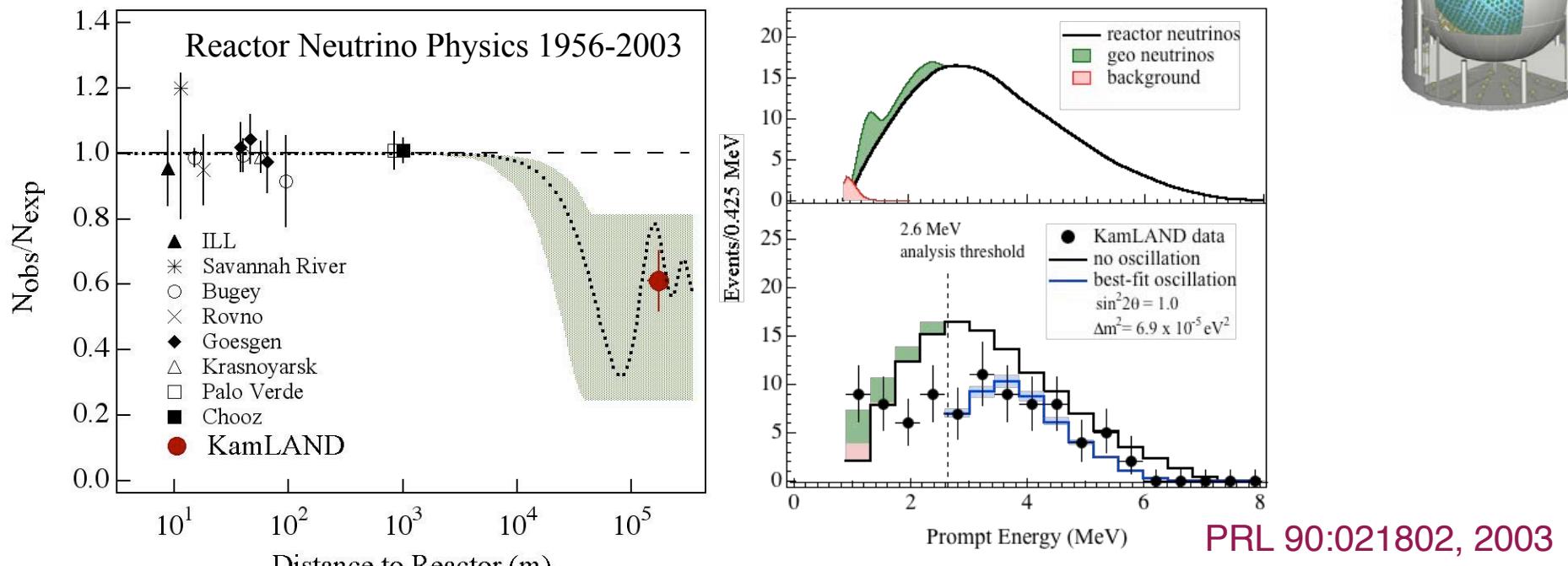
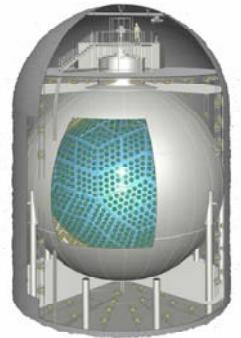
$R < 5 \text{ m}$

$0.5 < |dT| < 660 \text{ msec}$

$|dR| < 1.6 \text{ m}$

$|dZ| > 1.2 \text{ m}$

First Direct Evidence for Reactor $\bar{\nu}_e$ Disappearance



Observed

54 events

syst err. 6.4%

Expected

162 ton \cdot yr, $E_{\text{prompt}} > 2.6 \text{ MeV}$
 $86.8 \pm 5.6 \text{ events}$

Background

accidental

${}^9\text{Li}/{}^8\text{He}$

fast neutron

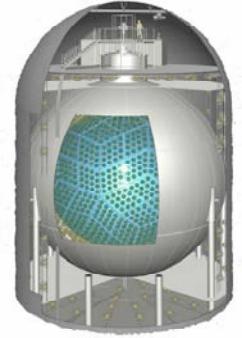
$1 \pm 1 \text{ events}$

0.0086 ± 0.0005

0.94 ± 0.85

< 0.5

KamLAND provides evidence for neutrino oscillations together with solar experiments.

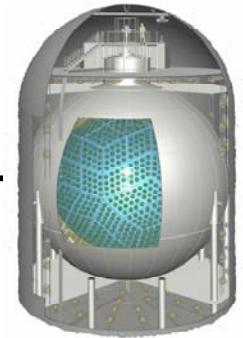


KamLAND - Systematic Uncertainties

E > 2.6 MeV

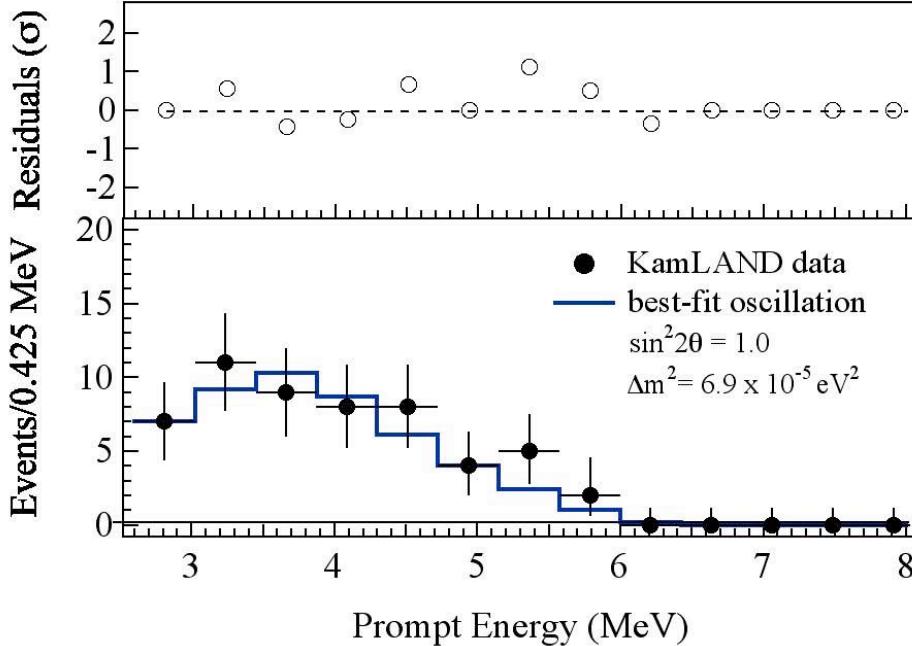
	%	
Total liquid scintillator mass	2.1	• volume calibration
Fiducial mass ratio	4.1	• energy calibration or analysis w/out threshold
Energy threshold	2.1	• detection efficiency
Tagging efficiency	2.1	
Live time	0.07	
Reactor power	2.0	<i>given by reactor company, difficult to improve on</i>
Fuel composition	1.0	
$\bar{\nu}_e$ spectra	2.5	<i>theoretical, model-dependent</i>
cross section	0.2	
Total uncertainty	6.4 %	

Is the KamLAND Neutrino Spectrum Distorted?



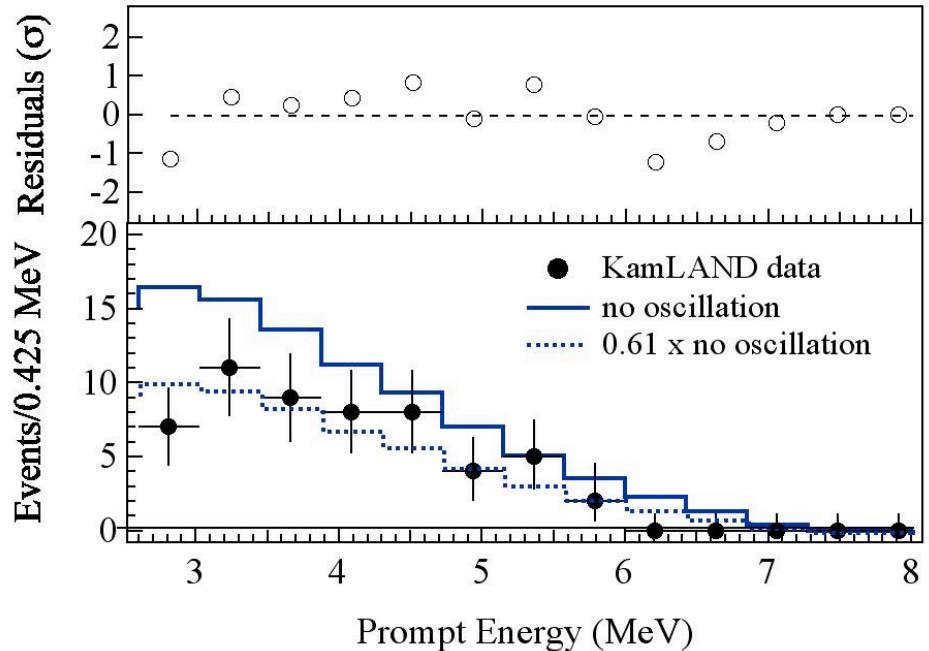
2- ν oscillation: best-fit

No oscillation, flux suppression



$$\chi^2 / 8 \text{ d.o.f} = 0.31$$

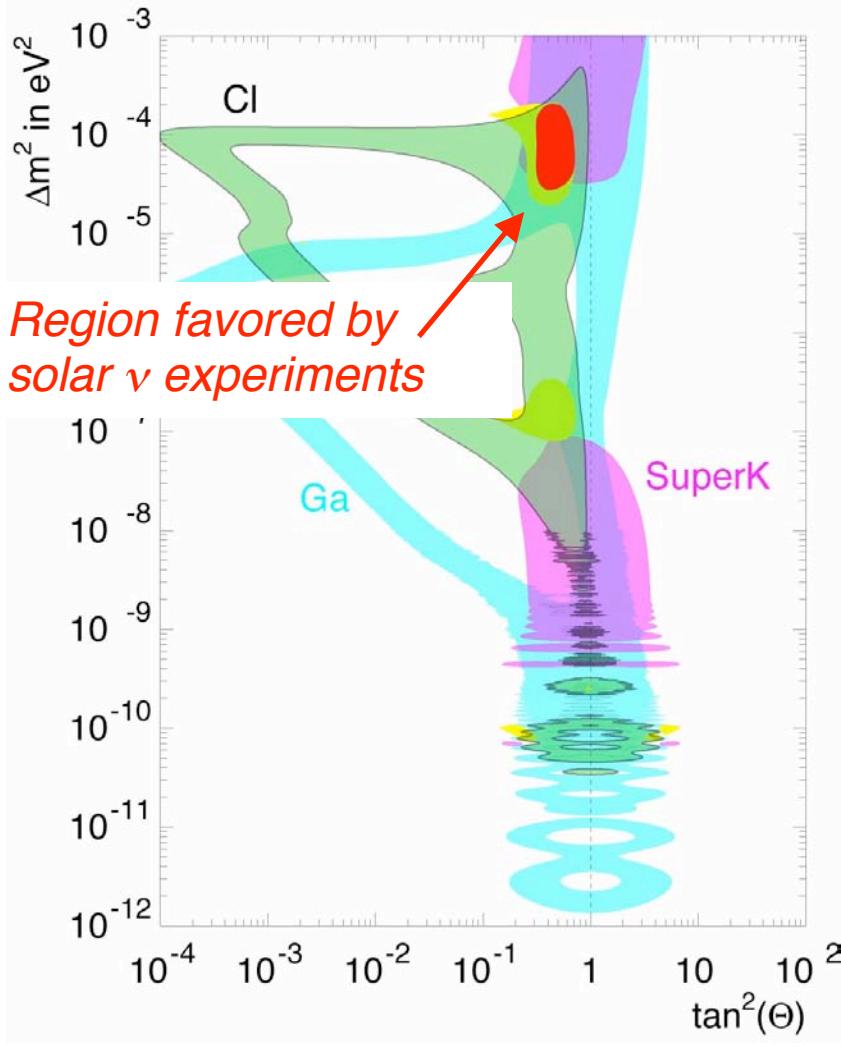
Data and best oscillation fit
consistent at 93% C.L.



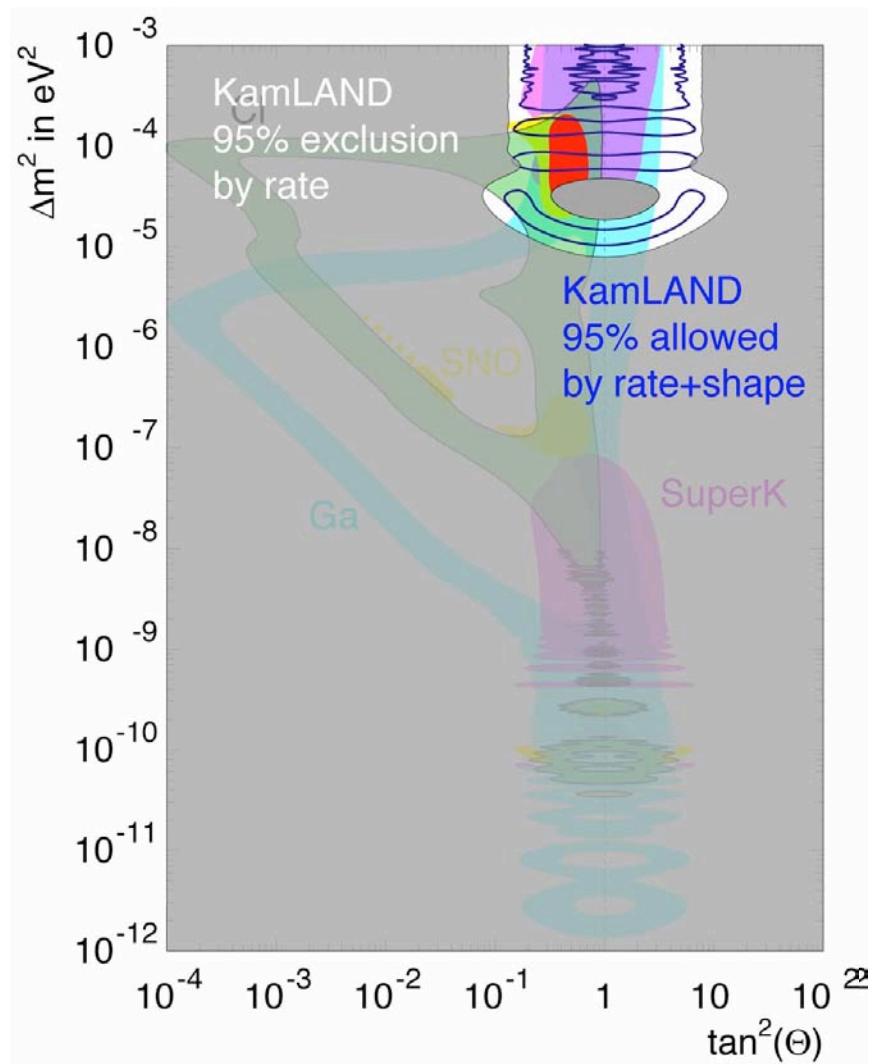
Data and best oscillation fit
consistent at 53% C.L. as
determined by Monte Carlo

Oscillation Parameters *Before* and *After* KamLAND

Before KamLAND

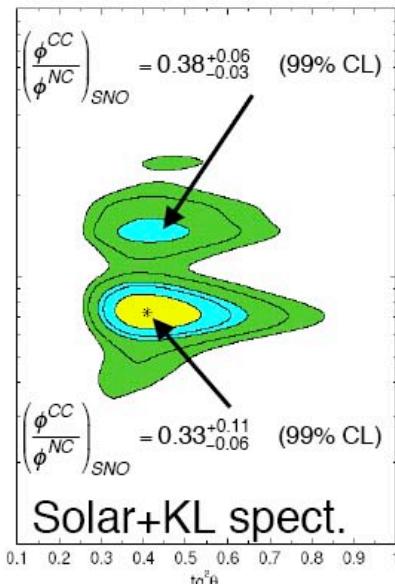
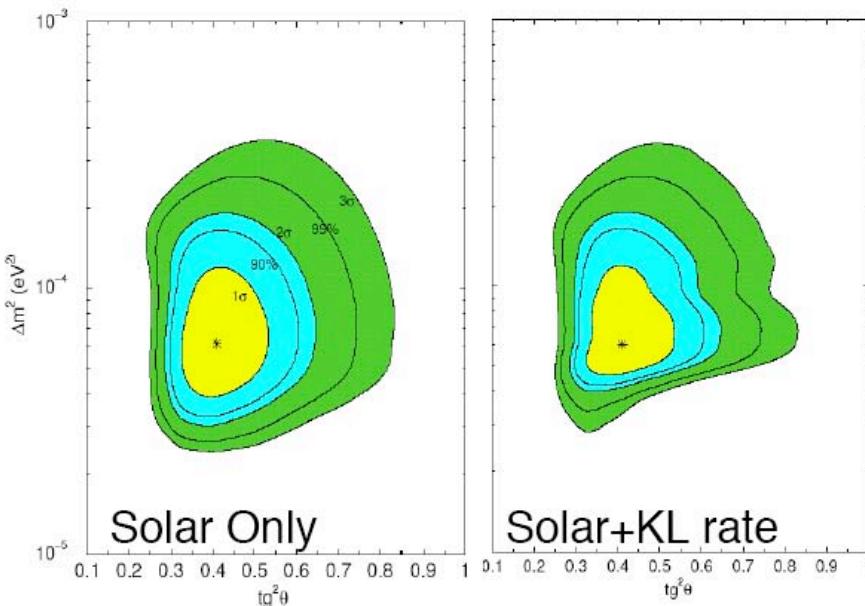


After KamLAND

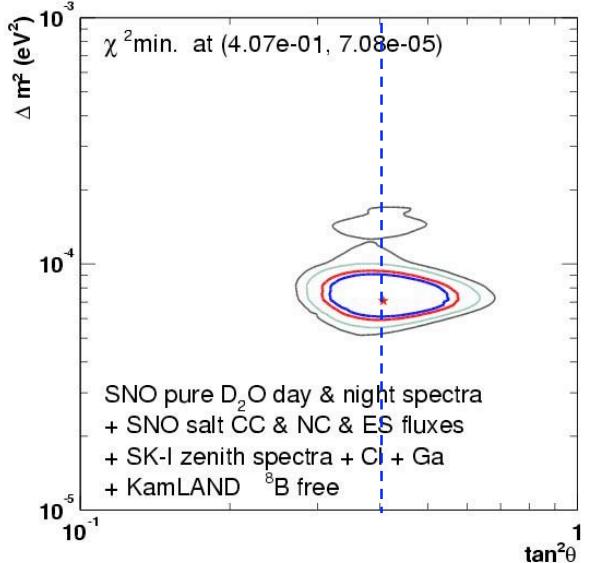


Determination of Oscillation Parameters Δm_{12}^2 , θ_{12}

Before SNO-Salt



With SNO-Salt



de Holanda & Smirnov, hep-ph/0205241, hep-ph/0212270

Assume CPT

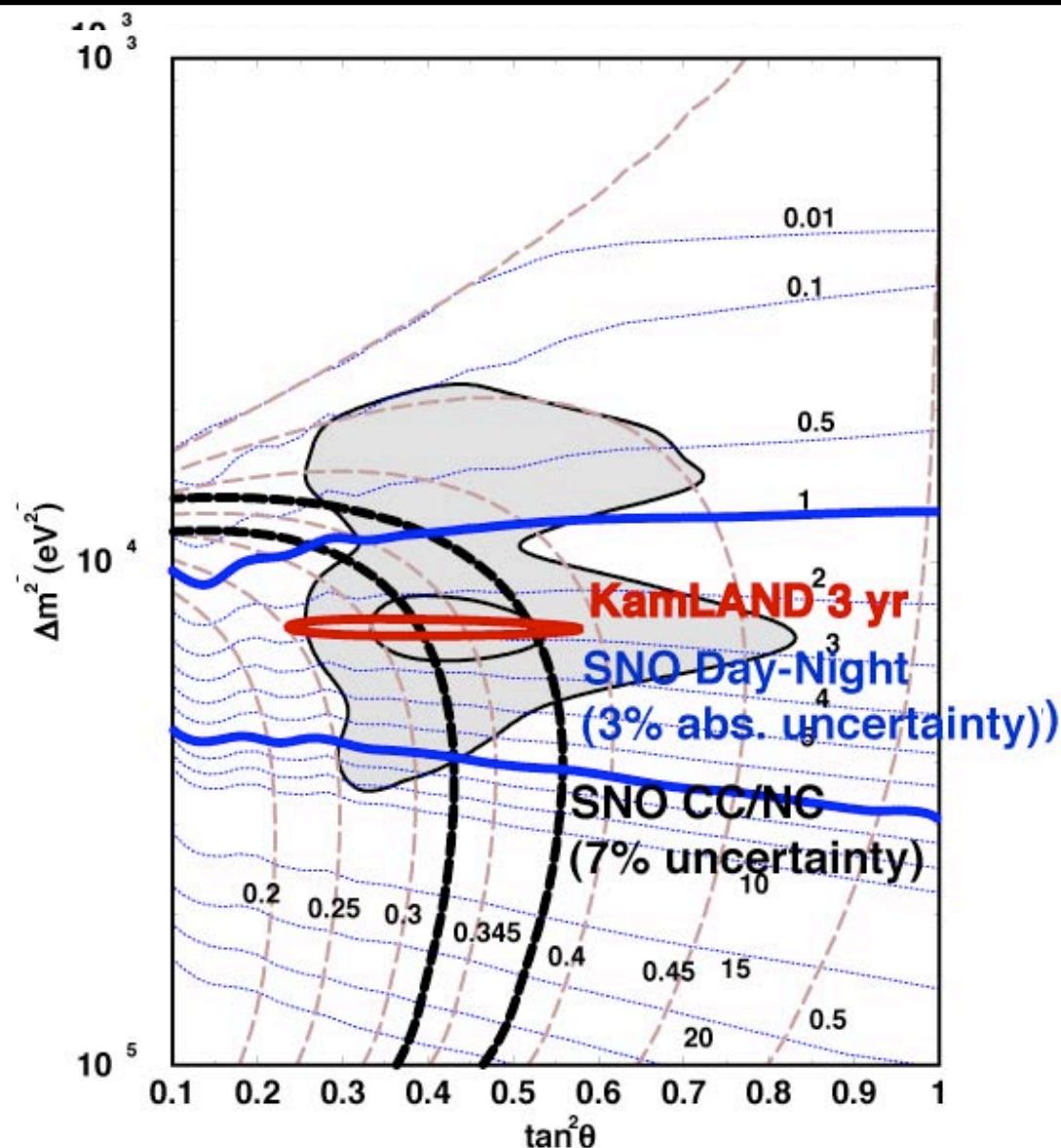
$$|\Delta m_\nu^2 - \Delta m_{\bar{\nu}}^2| < 1.3 \times 10^{-3} \text{ eV}^2 \text{ at } 90\% \text{ CL}$$

- LMA I only at > 99% CL
- Maximal mixing ruled out (5.4σ)

Possible Sterile Admixture?

Defining θ_{12} , Δm_{12}^2 with SNO and KamLAND

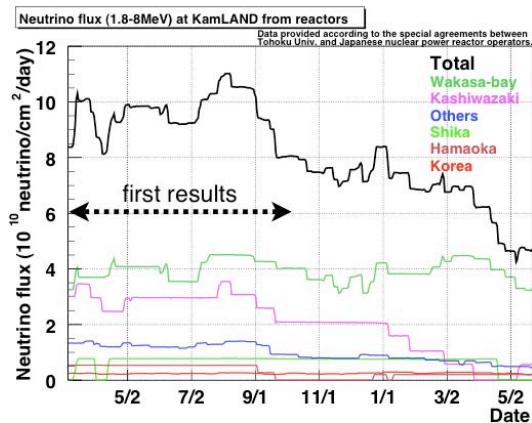
Future Impact of Non-Accelerator Experiments on θ_{12} and Δm_{12}^2



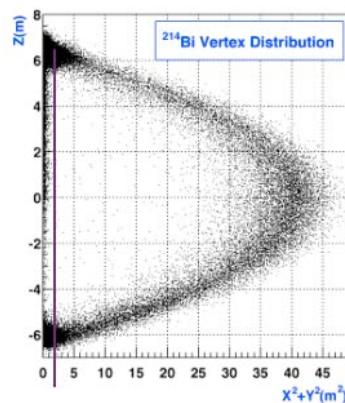
de Holanda et al., hep-ph/0212270,
Barger et al., hep-ph/0204253

What's next for KamLAND?

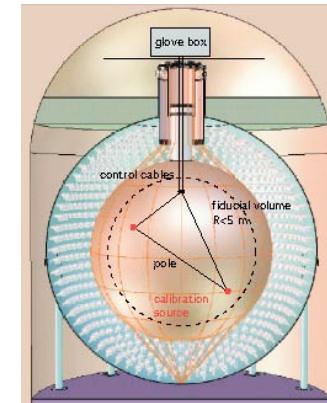
Continued Running



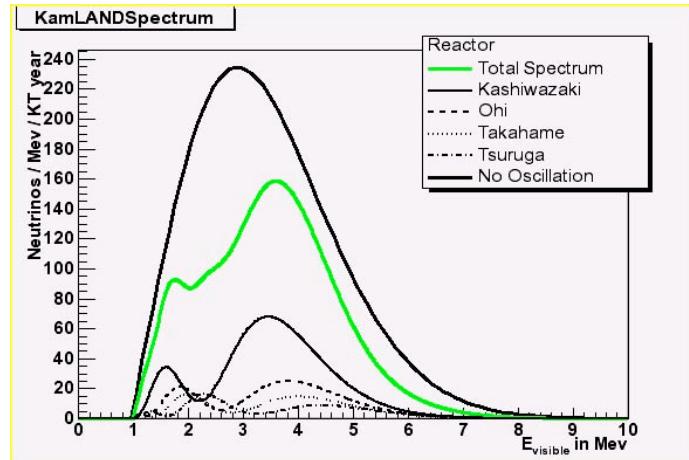
Enlarge Fiducial Volume



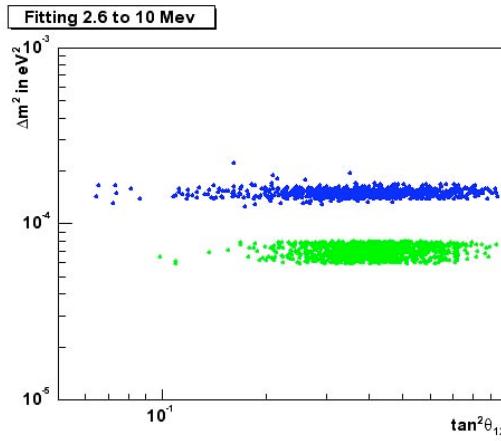
Improve Calibration



Search for Spectral Distortions



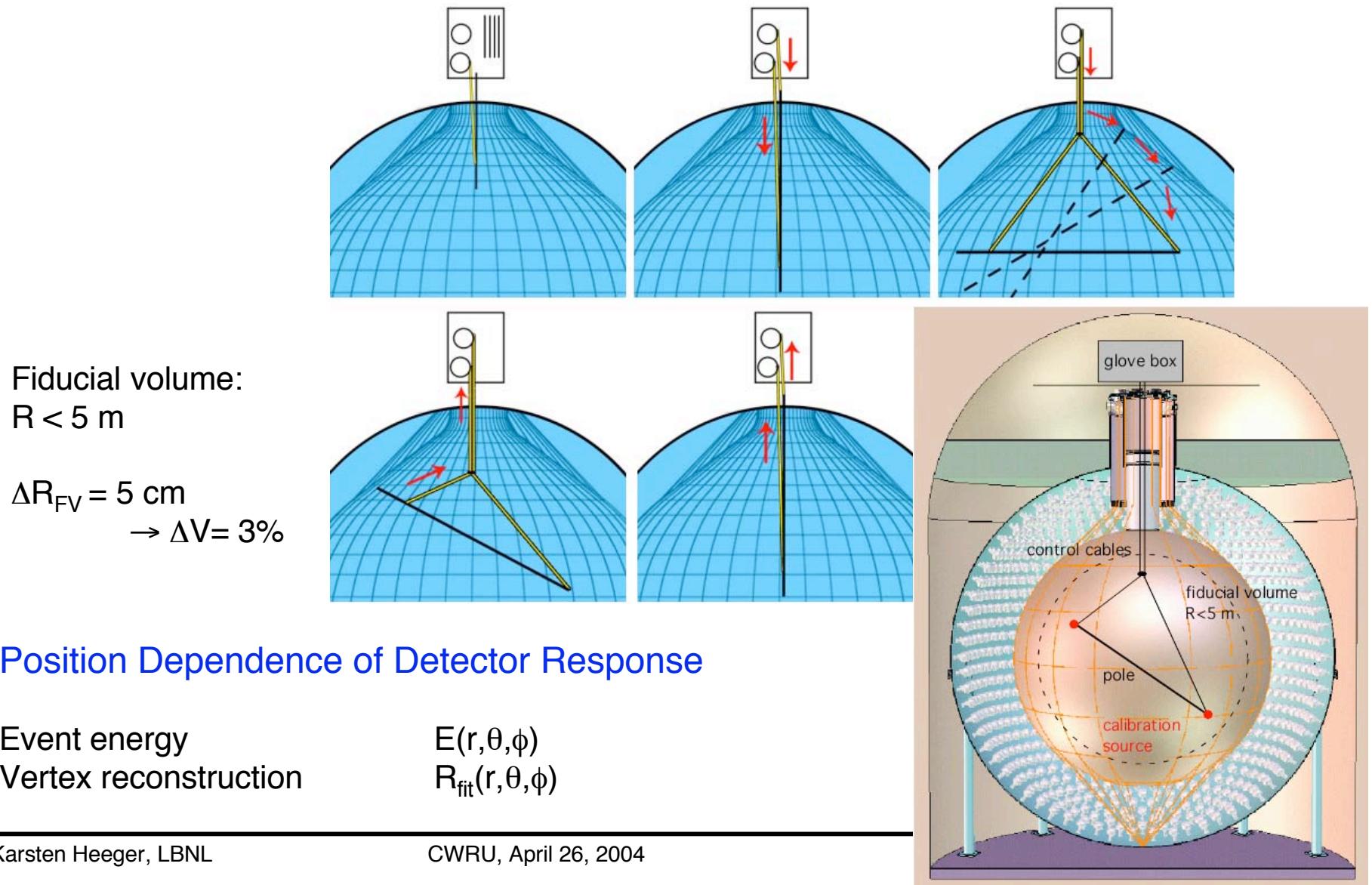
Improve Δm^2 and θ_{12}



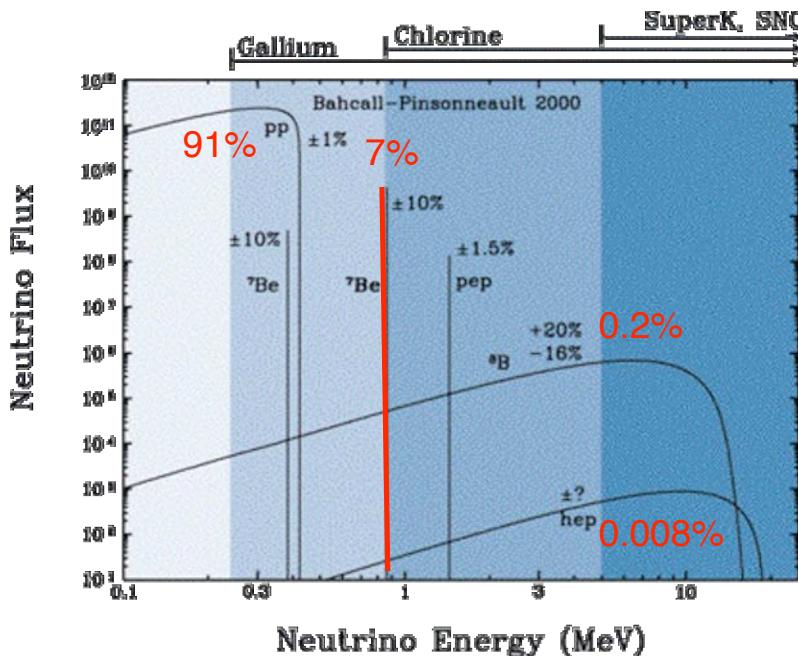
Search for geo-, supernova, and relic-supernova anti-neutrinos.
Nucleon decay studies.

KamLAND Off-Axis Calibration

Calibration throughout entire detector volume

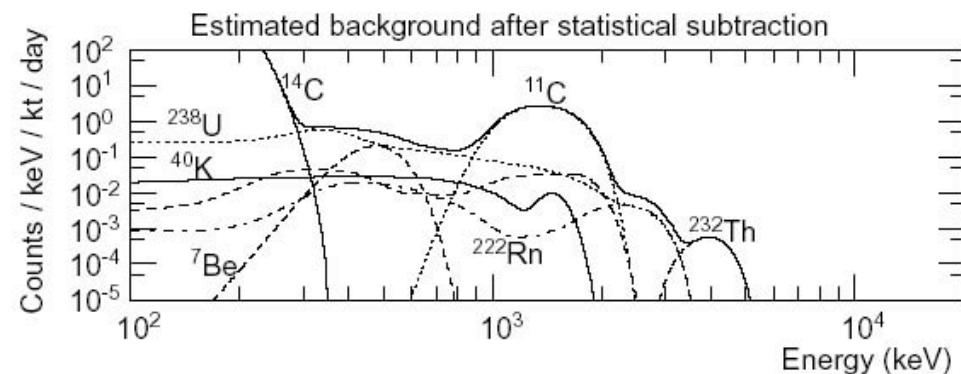


Detecting ${}^7\text{Be}$ Solar Neutrinos at KamLAND

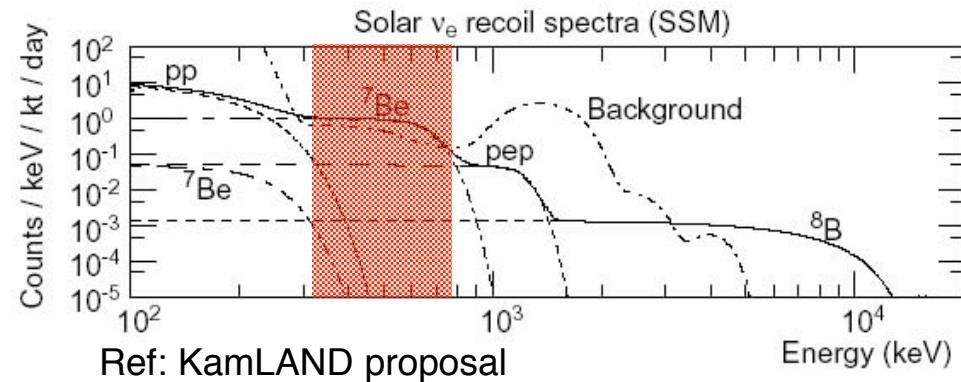


Direct detection of solar ${}^7\text{Be}$ neutrinos through elastic scattering

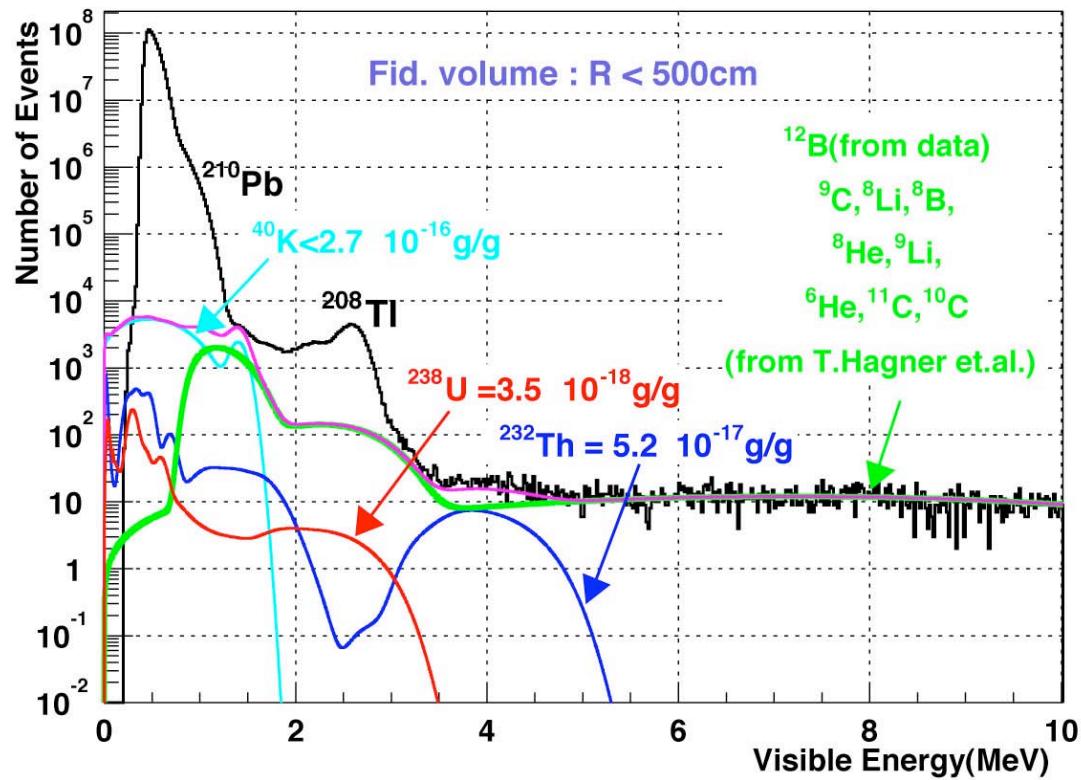
→ singles signal



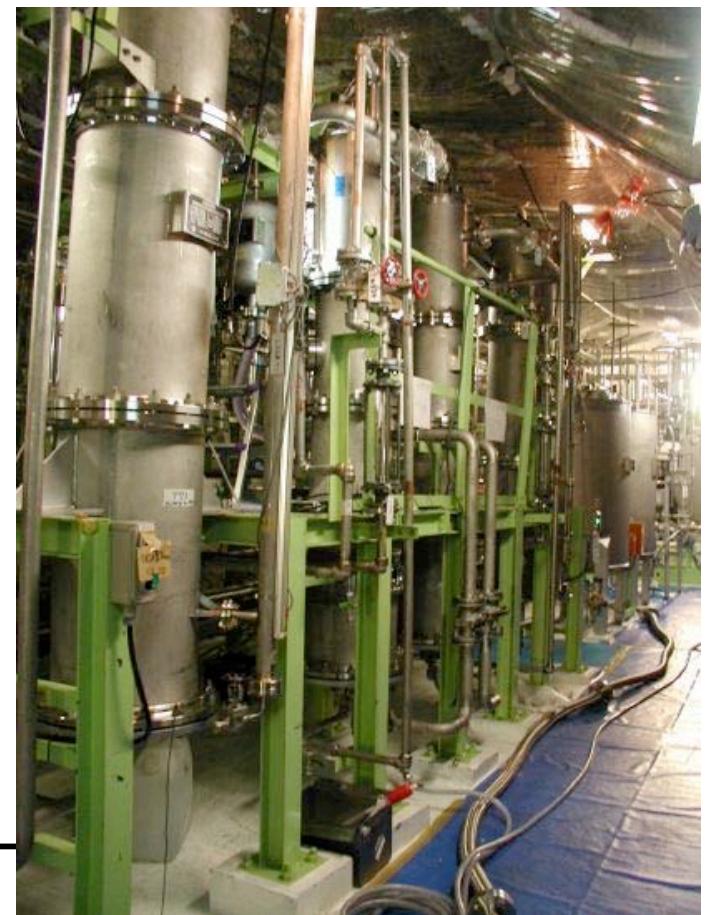
- ${}^7\text{Be} \nu_e$ measurement can improve solar models.
- Unlikely to improve on θ_{12} .
- Checks oscillation prediction of ${}^7\text{Be} \nu_e$ flux.



A Background Challenge: ${}^7\text{Be}$ Solar Neutrinos at KamLAND



- Backgrounds in the ${}^7\text{Be}$ signal region currently about 10^6 times too high
- Working on purification methods to remove
 ${}^{85}\text{Kr}$ (from nitrogen used in purification)
 ${}^{210}\text{Pb}$, ${}^{210}\text{Po}$ (from decay of radon)



We have learned ...

- ν transform flavor
- Solar ν_e change primarily to other active ν 's
 - if oscillations, mixing angle θ_{12} is large but not maximal and $\Delta m_{12} \sim 7 \times 10^{-5} \text{ eV}^2$ (LMA solution)
 - matter predicted to play a role in transformation
 - other modes for solar neutrino flavor transformation (sterile, RSFP, CPT ...) can play only a subdominant role.
- Atmospheric ν data explained extremely well by oscillations
 - primarily $\nu_\mu \rightarrow \nu_\tau$ conversion
 - mixing angle θ_{23} is very large, possibly maximal
 - $\Delta m^2 \sim 2 \times 10^{-3} \text{ eV}^2$

“...convincingly show that the flavor transitions of solar neutrinos are affected by Mikheyev-Smirnov-Wolfenstein (MSW) effects”

G.L. Fogli et. al, hep-ph/0309100

The Neutrino Mixing Matrix

U_{MNSP} Neutrino Mixing Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \underbrace{\quad}_{\text{atmospheric, K2K}} \underbrace{\quad}_{\text{reactor and accelerator}} \underbrace{\quad}_{\text{SNO, solar SK, KamLAND}} \underbrace{\quad}_{\text{0v}\beta\beta}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Dirac phase}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana phases}} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

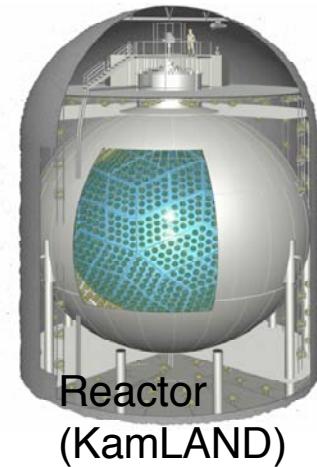
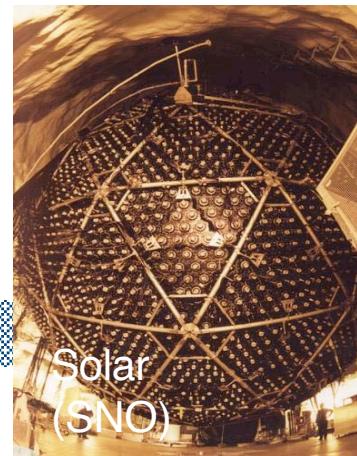
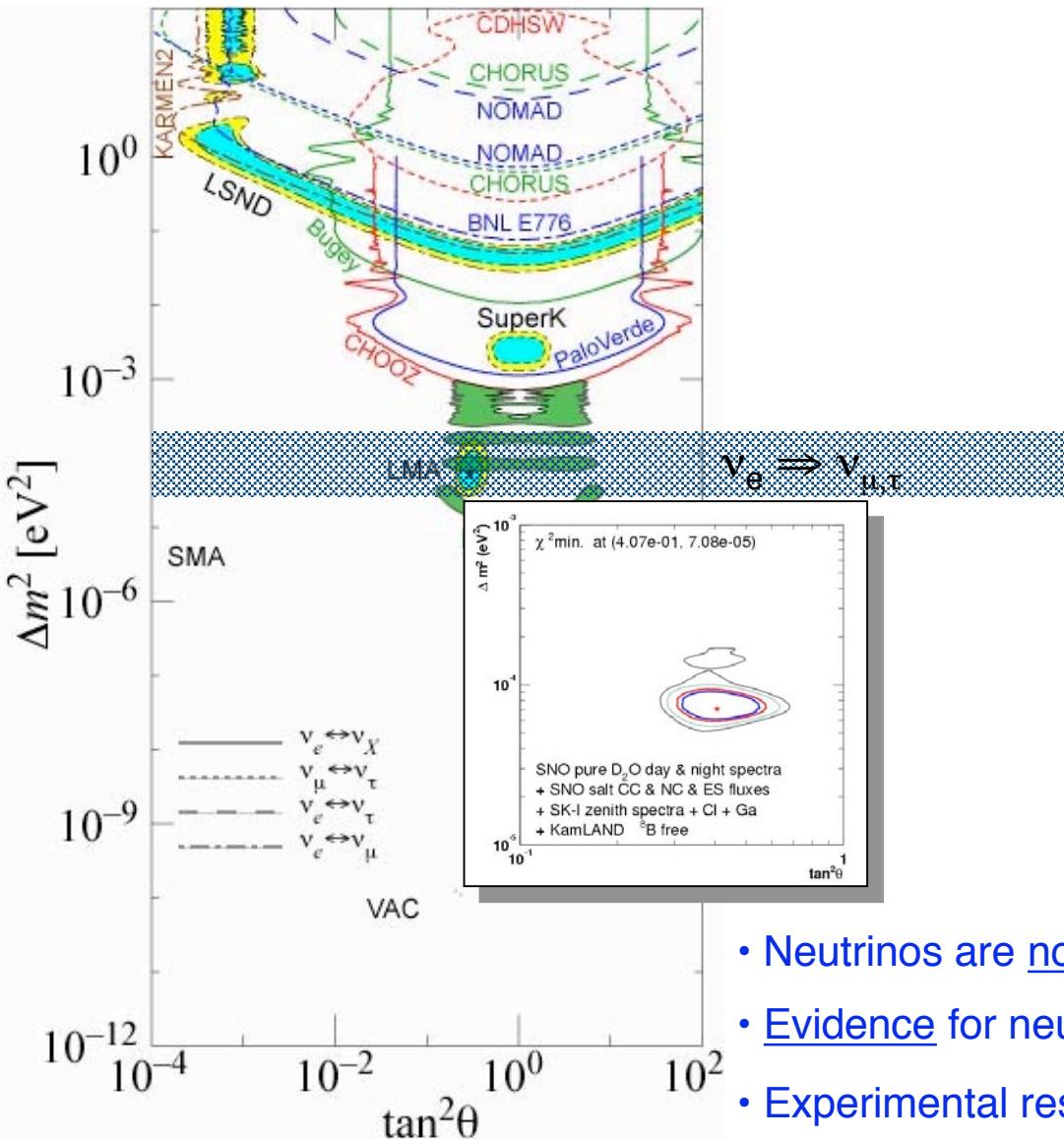
Dirac phase

Majorana phases

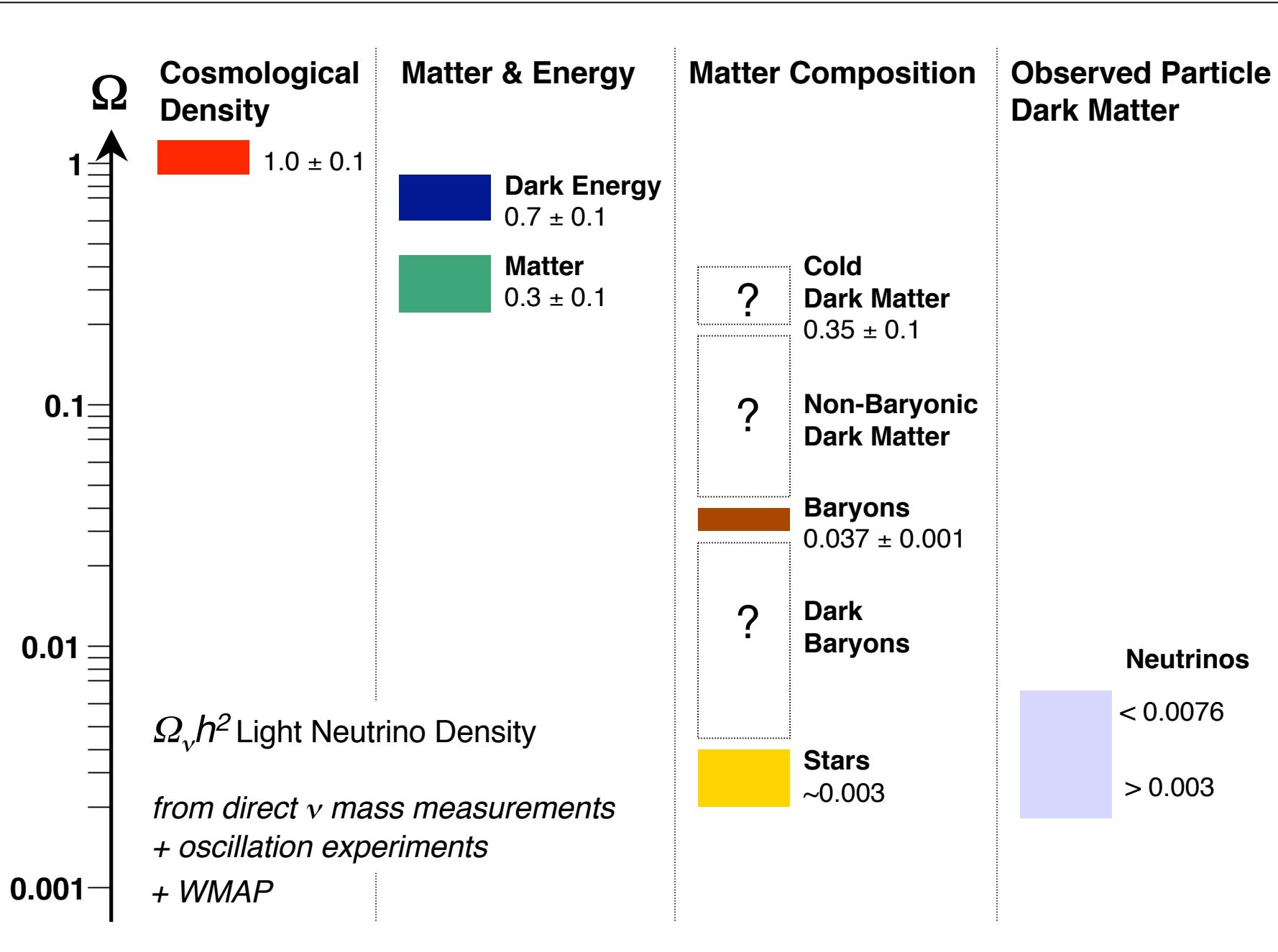
$\theta_{23} = \sim 45^\circ$ $\tan^2 \theta_{13} < 0.03$ at 90% CL $\theta_{12} \sim 32^\circ$

maximal *small ... at best* *large*

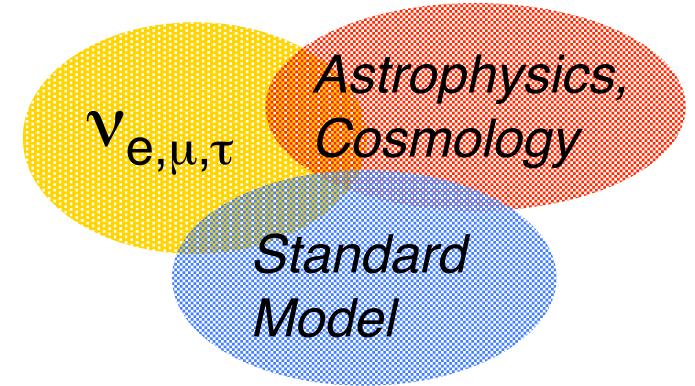
Oscillation Interpretation of Solar/Reactor Neutrino Data



- Neutrinos are not massless
- Evidence for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that neutrinos oscillate

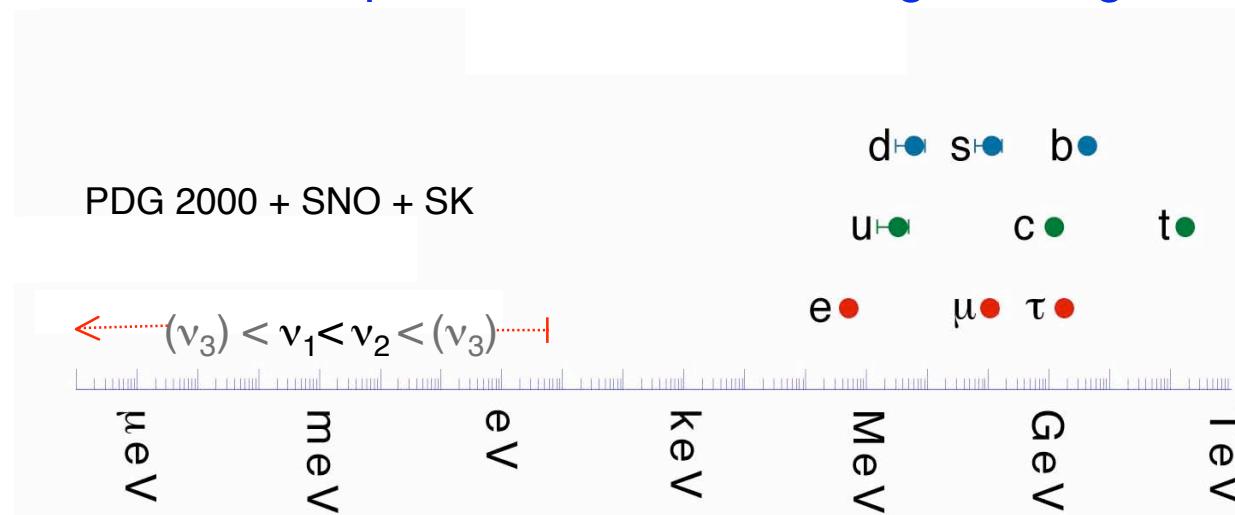


Summary



- The Solar Neutrino problem was caused by **neutrino mixing**.
- Neutrinos have **mass**.
- Neutrinos have **mixed flavor**, and **they oscillate**.
- Evidence that **Standard Model of Particle Physics** is incomplete.
- Unlike the quark sector, the **lepton sector exhibits large mixing**.

Fermion Masses



Open Questions in Neutrino Physics

- Is $U_{13} = 0$?
 - Is there CP violation for neutrinos?
 - What are the values of Δm^2 , U_{ij} ?
-
- Is U 3-dimensional? 4? 6? ∞ ?
 - or, is the 3-D version unitary?
 - or, are there sterile ν ?

 - What are the absolute masses?
 - What is the level ordering of 2,3 (or 1,3)?
 - Are ν 's Dirac or Majorana particles?

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